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Inter laboratory comparison on Industrial Computed Tomography

CIA-CT comparison. Reference Measurements

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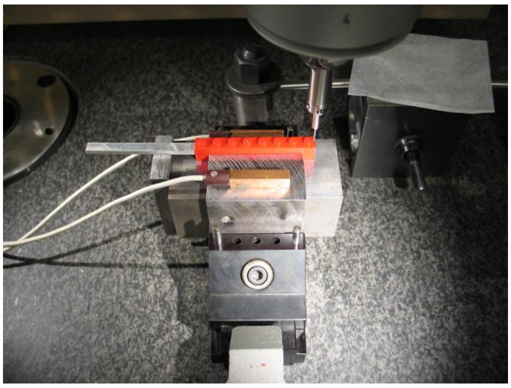
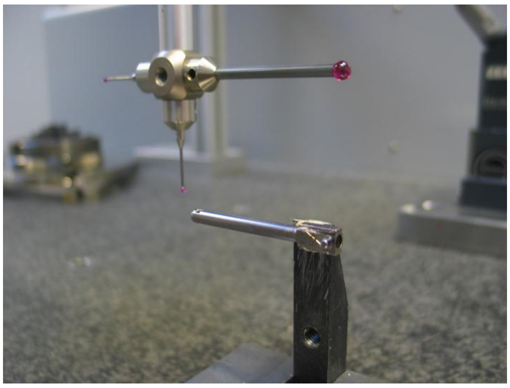
CIA-CT comparison

Inter laboratory comparison on Industrial Computed Tomography

Reference Measurements

September 2013

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1. Introduction

The ‘CIA-CT comparison - Inter laboratory comparison on industrial Computed Tomography” was organized by DTU Department of Mechanical Engineering, Centre for Geometrical Metrology (CGM), within the Danish project “Centre for Industrial Application of CT scanning - CIA-CT”, co-financed by the Danish Ministry of Science, Technology and Innovation.

The comparison has aimed at collecting information about measurement performance in state-of the-art industrial X-ray Computed Tomography (CT). Since CT has entered the field of manufacturing and coordinate metrology, evaluation of the uncertainty of measurement with assessment of all influence contributors has become a most important challenge related to the establishment of traceability. This investigation focuses mainly on operator influences on the measurement results.

Two items were used, selected among common industrial parts: a polymer part (Item 1) and a metal part (Item 2). Item 1 is a polymer brick from LEGO. The item is made of Acrylonitrile Butadiene Styrene (ABS) featuring eight knobs in one row. Item 2 is a metallic tubular component from the medical industry. The two items are considered more similar to industrial parts commonly measured in industry, in terms of material, dimensions and geometrical properties, than reference artefacts commonly used for calibration and verification of CT scanners. The two items are shown in Figure 1 and Figure 2. The presentation of items, measurements, measurands and measuring conditions can be found in [Technical Protocol]. Different measurands were considered, encompassing diameters, roundness, and lengths.

All together, 30 plastic items and 29 metal items were manufactured from industrial production and measured at CGM. 27 sets were circulated in parallel, one set per participant. Reference values for all 30 plastic- and 29 metal items were provided by CGM using coordinate measuring machines. Their reference values with expanded uncertainties were determined. Stability of items was documented through comparison of measurements before and after the circulation.

This report contains details on reference measurements carried out by the coordinator before and after circulation.

In order to judge the agreement between reference measurements before and after circulation, the E_n value normalised with respect to the calculated uncertainty was computed according to ISO guidelines [ISO/IEC 17043, 2010], see Equation 1. If $|E_n| < 1$, agreement between measurement results is proven while it is not the case if $|E_n| \geq 1$.

$$E_n = \frac{x_{after} - x_{before}}{\sqrt{U_{after}^2 + U_{before}^2}} \qquad (1)$$

Here, x_{after} is the measurement obtained after circulation and x_{before} is the reference value before the circulation, while U_{after} and U_{before} are the corresponding expanded uncertainties (k=2).

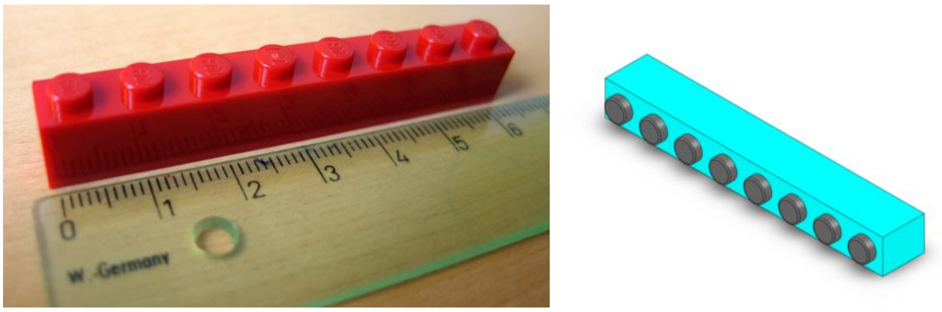


Figure 1: Item 1 (left) and 3D CAD model (right).

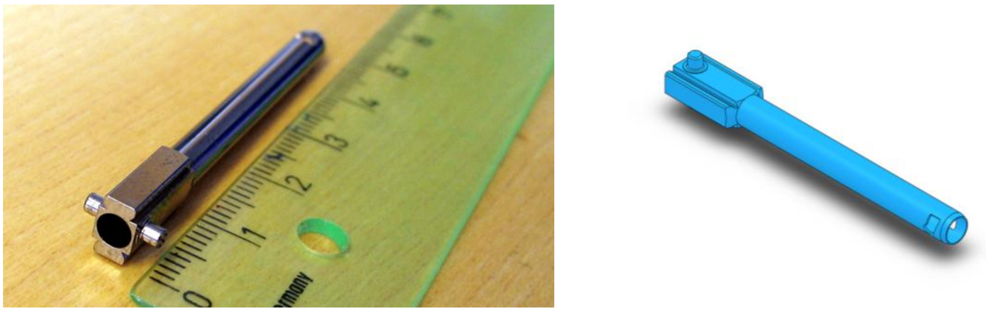


Figure 2: Item 2 (left) and 3D CAD model (right).

2. Reference measurements Item 1

This chapter concerning reference measurements is divided in the following sections: Measuring conditions, Data processing, Reference values, Analysis of reference measurement data, Comparison of values after circulation with reference values before circulation, and Conclusion.

2.1. Measuring conditions

The measuring conditions are divided in five subcategories: Equipment, Traceability, Used software, Dates of measurements, and Measurement procedure.

2.1.1. Equipment

The coordinate measuring machine used at CGM to measure the 30 sets of Item 1 is a mechanical CMM equipped with a static probe. The CMM is of the type Zeiss UPMC 850 CARAT (Figure 3), with some of its specifications shown in Table 1. The CMM is placed in a temperature controlled room (T = 20 °C ± 0.4 °C and a maximum RH of 60 %).

Figure 3: CMM of the type UPMC 850 CARAT placed at CGM.

Table 1: Some selected features for Zeiss UPMC 850 CARAT.

Features for Zeiss UPMC 850 CARAT	
Measuring volume	(x, y, z) = 820mm x 700mm x 600mm
MPE	One-dimensional length measuring uncertainty: u1 = (0.4 + L / 900) µm Three-dimensional length measuring uncertainty: u3 = (0.8 + L / 600) µm

2.1.2. Traceability

The equipment and reference artifacts used to generate traceability are reported in Table 2. A zerodur plate and a calibration sphere were used as length and diameter/roundness references, respectively.

Table 2: Used equipment and reference artifacts to generate traceability.

Object	Certificate
Calibration sphere, Ø8 mm	Carl Zeiss Certificate 2715 Dated: 10th August 2012
Zerodur hole plate, 50 mm between holes	PTB Certificate 4758 PTB 05 Dated: 16th September 2005
Temperature system	Brock & Michelsen Certificate S020355 Dated: 1st May 2012
Zeiss UPMC 850 CARAT	Brock & Michelsen Certificate S020355 Dated: 1st May 2012

Figure 4: Calibration sphere, Ø8 mm.

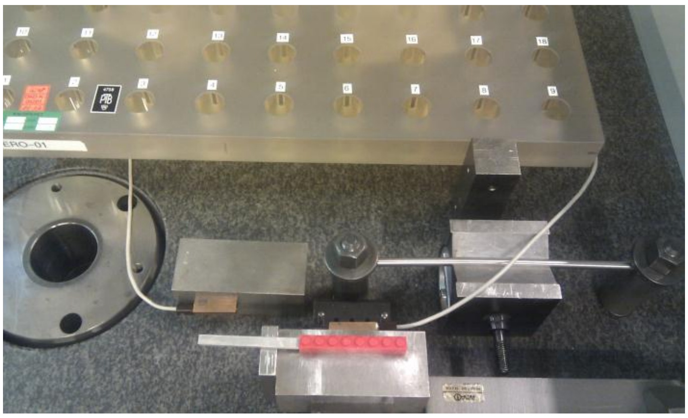


Figure 5: Zerodur plate.

2.1.3. Used software

The used software is shown in Table 3.

Table 3: Used software.

Software
UMESS/UX Software Rev 8.4.2

2.1.4. Dates of measurement

Reference measurements were carried out by CGM, before circulation (1st round) and after circulation (2nd round) as indicated in Table 4. Due to temperature problems in the temperature controlled room after circulation, a new series of reference measurements were performed (3rd round).

Table 4: Dates of measurement at CGM.

Item 1	Item ID	Month	Year
Measured at CGM before circulation (1st round)		December	2012
		May	2013
Measured at CGM after circulation (2nd round)		May	2013
		June	2013
Measured at CGM after circulation (3rd round)		August	2013

2.1.5. Measurement procedure

A presentation of Item 1, measurements details, datums to be used, and measurands can be found in [Technical Protocol], and is summarized in Table 5 and Figure 6. The selected geometrical features were length, diameter and roundness. An example on the applied measurement protocol can be found in Appendix based on a transcript from the CMM software. Diameter and roundness measurements are based on approximately 2400 points through a continuous moving contact with the part surface. *D1* and *R1* were calculated for the unfiltered profiles as well as for profiles filtered using 150 UPR (undulations per rotation).

The measurement set-up is illustrated in Figure 7. The 30 samples were measured using a probe with Ø 1.0 x 15 mm and a probing force of 0.1 N.

The location of the temperature sensors is shown in Figure 7. All 30 samples were acclimated in one week. Temperature difference between machine and workpiece is neglected because of acclimatisation. It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.5 °C. The temperature was registered before each measurement.

The 30 samples were handled using gloves by authorised personnel and carefully treated in order to prevent damages. The 30 samples were cleaned gently using a soft brush. The samples have been glued on a fixture for reference measurements using Loctite 406.

The probing repeatability was evaluated from 5 repeated measurements on a single sample.

Table 5: Item 1 – Overview of measurands; D1, R1 and L1 [Technical Protocol].

Identification		Description
Diameter,	*D1*	Diameter of knob at inlet *D1* - circle (GG) is measured 1 mm above datum A
Roundness,	*R1*	Roundness of knob at inlet *R1* - circle (LSCI) is measured 1 mm above datum A
Length,	*L1*	Distance between datum B and datum C 1 mm above datum A

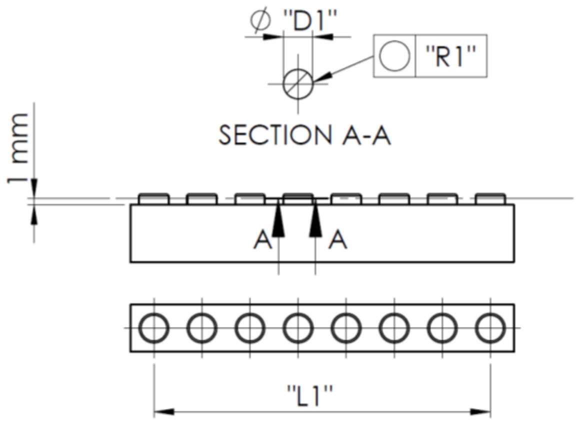


Figure 6: Item 1 – Overview of measurands; D1, R1 and L1.

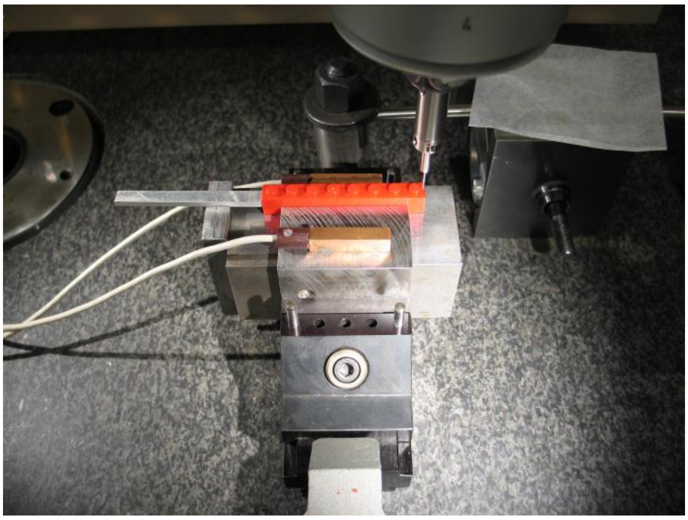


Figure 7: Measurement set-up for Item 1. Two temperature sensors are fixed on each side parallel to the item.

2.2. Data processing

Data processing is divided in four subcategories: Uncorrected measurement results, Systematic errors, Measurement uncertainty, and Summarized bias and uncertainty budgets.

2.2.1. Uncorrected measurement results

The complete measurements including systematic error and uncertainty can be written as given in Equation 2.

$$Y = \overline{Y} - b \pm U(Y) \tag{2}$$

Here, Y is the final result, $\overline{Y}$ the average from repeated measurements, b the total bias (systematic error) and $U(Y)$ is the expanded uncertainty (k=2).

An uncorrected measurement example for Item 1 ID no. 2 before circulation is given in Appendix for the three measurands: diameter *D1*, roundness *R1* and length *L1*. Furthermore, the uncorrected data for the reference artifacts are shown in Appendix too.

2.2.2. Systematic errors

The total systematic error can be written as the summation of all the systematic errors as given in Equation 3.

$$b = \sum_{i=1}^{n} b_i \tag{3}$$

For estimation of the systematic errors, the following components in Table 6 are included in the systematic error for Item 1. Furthermore it is indicated with a X which systematic errors, which are considered for each given measurand for Item 1. Regarding to the compensation of systematic deviation due to the measuring force, measurements were compensated for deflection of the styli and deflection of the sample. It is assumed that the temperature deviation from standard reference temperature for workpiece and reference artifacts can be neglected, since the used software corrects for temperature and expansion. Note that no compensation of systematic deviation due to reference artifact (calibration sphere, Ø8 mm) is made for *D1*, because the size of the calibration sphere is measured and adjusted to the reference value from the certificate.

Table 6: List of the systematic errors for the measuring of the reference measurements at CGM.

No.	Category	Symbol	Involved uncertainty contributions	Measurand		
				D1	***R1***	***L1***
1	Reference standard	$b_{r(2)}$	Compensation of systematic deviation due to reference artifact (zerodur plate, 100 mm)			X
2	Environment	$b_{e(1)}$	Compensation of systematic deviation due to measuring force (work piece)	X		

A bias budget example is given for Item 1 ID no. 2 before circulation in Appendix.

2.2.3. Measurement uncertainty

The PUMA approach [ISO 14253-2, 2011] is used, which is a simplification of GUM approach [ISO/IEC Guide 98-3, 2008]. Equations 4 and 5 are used.

$$U = k \cdot u_c \qquad (k = 2) \tag{4}$$

Here, U is the expanded uncertainty, u_c is the combined standard uncertainty and k is the coverage factor ($k = 2$ for a coverage probability of 95 %). The considered uncertainty contributors are given in Equation 5.

$$U = k \cdot \sqrt{{u_r}^2 + {u_{rep}}^2 + {u_w}^2 + {u_{e(1)}}^2 + {u_{e(2)}}^2 + {u_{e(3)}}^2 + {u_{e(4)}}^2 + {u_{e(5)}}^2 + {u_p}^2} \tag{5}$$

The following components from Equation 5 are described in Table 7 and included in the budget for Item 1. Note that the uncertainty components are divided in two categories: type A and type B. Furthermore it is indicated with a X which uncertainty contributions, which are considered for each given measurand for Item 1. For the cases of roundness it is assumed that the compensation coming from expansion coefficient can be neglected. Note that the uncertainty is assumed to be the same for unfiltered profiles as well as for profiles filtered using 150 UPR, where the calculations are based on profiles filtered using 150 UPR.

Table 7: List of the uncertainty contributors for the measuring uncertainty budget of the reference measurements at CGM.

No.	Category	Symbol	Involved uncertainty contributions	Type	Measurand		
					D1	*R1*	*L1*
1	Reference standard	$u_{r(1)}$	Uncertainty component from calibration sphere, Ø8 mm	B	X	X	
		$u_{r(2)}$	Uncertainty component from zerodur plate, 100 mm	B			X
2	Measuring instrument	$u_{rep(1)}$	Uncertainty component from repeatability on calibration sphere, Ø8 mm	A	X	X	
		$u_{rep(2)}$	Uncertainty component from repeatability on zerodur plate, 100 mm	A			X
3	Workpiece	u_w	Uncertainty component from work piece	B	X	X	X
4	Environment	$u_{e(1)}$	Uncertainty component from temperature difference between workpiece and instrument	B	X		X
		$u_{e(2)}$	Uncertainty component from temperature deviation from standard reference temperature for instrument	B	X		X
		$u_{e(3)}$	Uncertainty component from temperature deviation from standard reference temperature for workpiece	B	X		X
		$u_{e(4)}$	Uncertainty component from workpiece expansion coefficient uncertainty	B	X		X
		$u_{e(5)}$	Uncertainty component from measuring force	B	X		
5	Procedure	u_p	Uncertainty component from measurement process	A	X	X	X

An uncertainty budget example is given for Item 1 ID no. 2 before circulation in Appendix.

The graphs in Figure 8, Figure 9 and Figure 10 give a sense of the distribution of the uncertainty components for Item 1 ID no. 2.

In Figure 8 it is clear that uncertainty component from work piece (u_w) is significant for *D1* for Item 1 ID no. 2, because its contribution exceeds the limit of significance of 10% from the sum of all uncertainty components.

In Figure 9 it is clear that uncertainty component from repeatability on calibration sphere ($u_{rep(1)}$), and uncertainty component from work piece (u_w) are significant for *R1* for Item 1 ID no. 2, because their contribution exceeds the limit of significance of 10% from the sum of all uncertainty components.

In Figure 10 it is clear that uncertainty component from temperature difference between workpiece and instrument ($u_{e(1)}$), and uncertainty component from temperature deviation from standard reference temperature for workpiece ($u_{e(3)}$) are significant for *L1* for Item 1 ID no. 2, because their contribution exceeds the limit of significance of 10% from the sum of all uncertainty components.

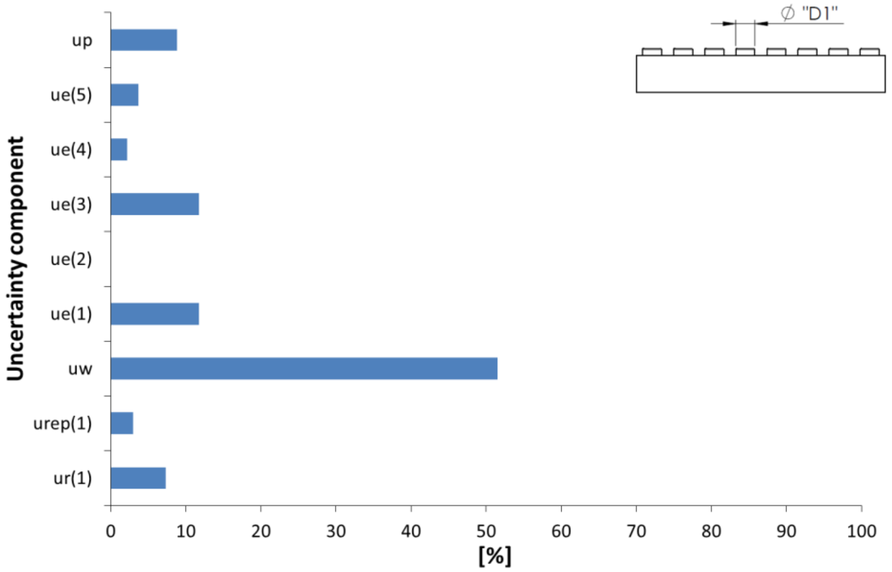


Figure 8: Item 1, ID no. 2, diameter D1, Distribution of uncertainty components.

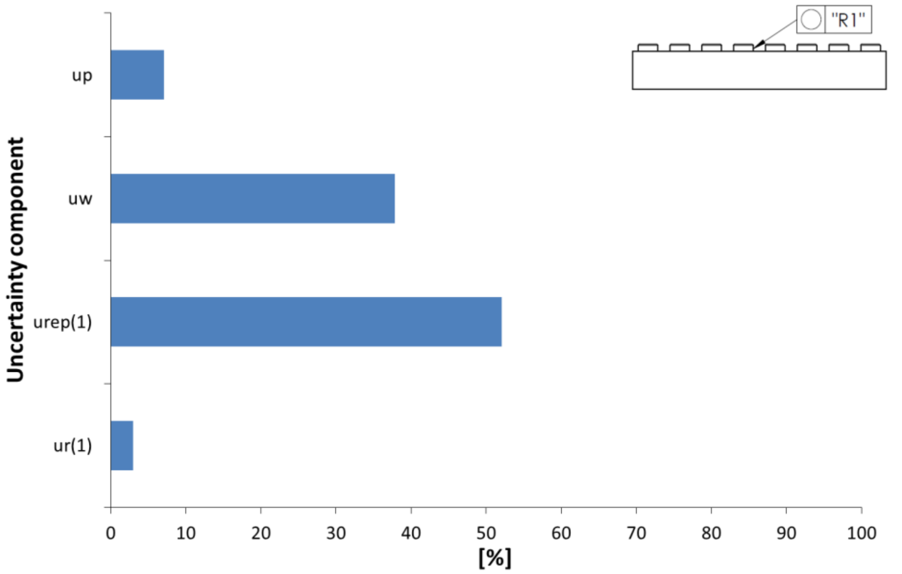


Figure 9: Item 1, ID no. 2, roundness R1, Distribution of uncertainty components.

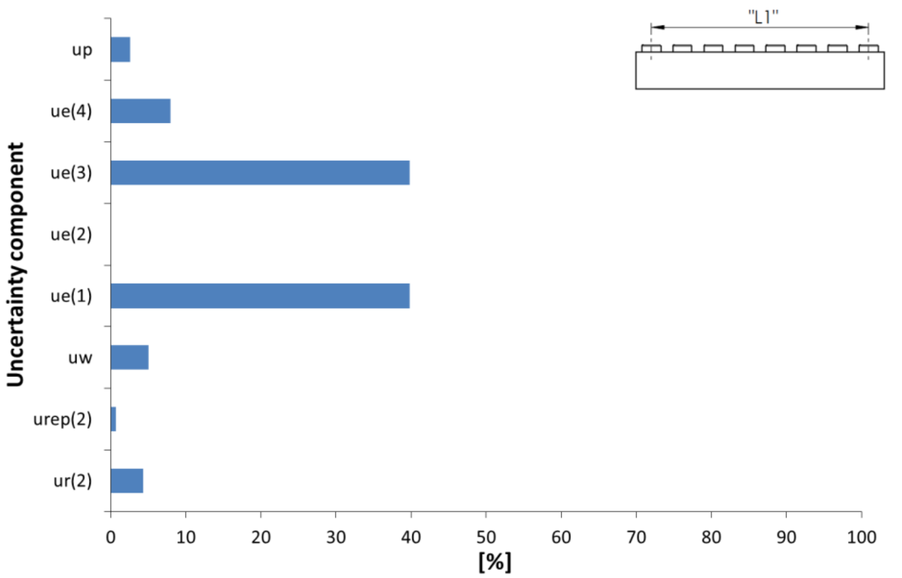


Figure 10: Item 1, ID no. 2, length L1, Distribution of uncertainty components.

2.2.4. Summarized bias and uncertainty budgets

2.2.4.1. Summarized bias and uncertainty budgets examples for Item 1 ID no. 2 before circulation

2.2.4.1.1. Item 1, ID no. 2, Length L1

A summarized overview example of a bias and uncertainty budget can be seen in Table 8 for Item 1 ID no. 2 for the case length *L1* before circulation.

Table 8: Item 1, ID no. 2, length L1, summarized overview of bias and uncertainty budgets.

Uncorrected measurement results				
Category	Measurand	Symbol	No. of measurements	Estimate [mm]
Average, from repeated measurements	*L1*	$\overline{Y}$	1	55.9582

Bias budget			
Category	Symbol	Systematic contributor	Estimate [µm]
Reference standard	$b_{r(2)}$	Compensation of systematic deviation due to reference artifact (zerodur plate, 100 mm)	2.20
Total bias	b	Compensation of total systematic deviation due to all biases	2.20

Uncertainty budget			
Category	Symbol	Uncertainty contributor	Estimate [µm]
Reference standard	$u_{r(2)}$	Uncertainty component from zerodur plate, 100 mm	0.20
Measuring instrument	$u_{rep(2)}$	Uncertainty component from repeatability on zerodur plate, 100 mm	0.03
Workpiece	u_w	Uncertainty component from work piece	0.23
Environment	$u_{e(1)}$	Uncertainty component from temperature difference between workpiece and instrument	1.86
	$u_{e(2)}$	Uncertainty component from temperature deviation from standard reference temperature for instrument	0.00
	$u_{e(3)}$	Uncertainty component from temperature deviation from standard reference temperature for workpiece	1.86
	$u_{e(4)}$	Uncertainty component from workpiece expansion coefficient uncertainty	0.37
Procedure	u_p	Uncertainty component from measurement process	0.12
Combined standard uncertainty	u_c	Combined standard uncertainty	2.68
Expanded uncertainty (k=2)	U	Expanded uncertainty	5.35

2.3. Reference values

The reference values before the circulation (1st round) for Item 1 and their corresponding uncertainties are shown in this section compared to the reference values after the circulation (for both the one in 2nd round and in 3rd round respectively). A measuring uncertainty at 95% level (k=2) is used for all CGM values. Furthermore the E_n values are informed.

2.3.1. Diameter D1 (un-filtered)

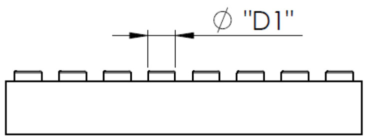


Table 9: Item 1 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 1, *D1*	1st round		2nd round		3rd round		2nd round versus 1st round	3rd round versus 1st round	3rd round versus 2nd round
ID no.	Y	U	Y	U	Y	U	|En| [-]	|En| [-]	|En| [-]
1	4.9030	0.0022	4.9018	0.0022	4.9029	0.0022	0.4	0.0	0.3
2	4.9046	0.0015	4.9036	0.0014	4.9046	0.0015	0.5	0.0	0.5
3	4.9027	0.0014	4.9020	0.0014	4.9026	0.0014	0.3	0.1	0.3
4	4.9046	0.0014	4.9038	0.0014	4.9044	0.0015	0.4	0.1	0.3
5	4.9041	0.0012	4.9036	0.0012	4.9045	0.0013	0.3	0.2	0.5
6	4.9008	0.0010	4.8992	0.0010	4.9011	0.0012	1.1	0.2	1.2
7	4.9046	0.0015			4.9045	0.0015		0.0	
8	4.9025	0.0023	4.9061	0.0009	4.9029	0.0022	1.5	0.1	1.3
9	4.9028	0.0022	4.9026	0.0022	4.9024	0.0023	0.1	0.1	0.1
10	4.9044	0.0016	4.9039	0.0016	4.9045	0.0016	0.2	0.0	0.2
11	4.9020	0.0021	4.9019	0.0021	4.9020	0.0020	0.0	0.0	0.0
12	4.9027	0.0023	4.9028	0.0022	4.9030	0.0022	0.0	0.1	0.0
13	4.9026	0.0013	4.9027	0.0013	4.9026	0.0014	0.1	0.0	0.0
14	4.9026	0.0014	4.9026	0.0014	4.9028	0.0014	0.0	0.1	0.1
15	4.9042	0.0015							
16	4.9044	0.0015	4.9045	0.0016	4.9047	0.0016	0.0	0.1	0.1
17	4.9044	0.0018	4.9044	0.0018	4.9036	0.0019	0.0	0.3	0.3
18	4.9042	0.0014	4.9043	0.0013	4.9037	0.0013	0.0	0.3	0.3
19	4.9007	0.0011	4.9005	0.0011	4.9011	0.0011	0.1	0.3	0.4
20	4.9007	0.0011	4.9004	0.0011	4.9007	0.0012	0.2	0.0	0.2
21	4.9036	0.0018	4.9036	0.0019	4.9042	0.0018	0.0	0.2	0.2
22	4.9002	0.0011	4.9011	0.0011	4.9013	0.0010	0.6	0.7	0.1
23	4.9042	0.0013	4.9044	0.0013	4.9046	0.0013	0.1	0.3	0.1
24	4.9041	0.0015	4.9046	0.0016	4.9049	0.0016	0.2	0.3	0.1
25	4.9059	0.0008	4.9003	0.0011	4.9007	0.0012	4.1	3.6	0.2
26	4.9039	0.0018	4.9046	0.0019	4.9043	0.0019	0.3	0.1	0.1
27	4.9041	0.0018	4.9047	0.0018	4.9046	0.0019	0.3	0.2	0.0
28	4.9040	0.0015			4.9051	0.0014		0.5	
29	4.9012	0.0019	4.9020	0.0020	4.9024	0.0019	0.3	0.4	0.1
30	4.9023	0.0013	4.9025	0.0013	4.9031	0.0014	0.1	0.4	0.3

AVG		0.0016		0.0015		0.0016	0.4	0.3	0.3
MAX		0.0023		0.0022		0.0023	4.1	3.6	1.3
MIN		0.0008		0.0009		0.0010	0.0	0.0	0.0

2.3.2. Diameter D1 (filter Gauss 150)

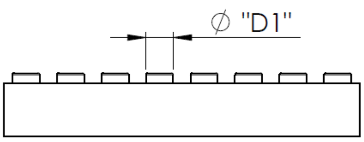


Table 10: Item 1 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 1, *D1*	1st round		2nd round		3rd round		2nd round versus 1st round	3rd round versus 1st round	3rd round versus 2nd round
ID no.	Y	U	Y	U	Y	U	|En| [-]	|En| [-]	|En| [-]
1	4.9030	0.0022	4.9018	0.0022	4.9029	0.0022	0.4	0.0	0.3
2	4.9046	0.0015	4.9036	0.0014	4.9046	0.0015	0.5	0.0	0.5
3	4.9027	0.0020	4.9020	0.0014	4.9026	0.0014	0.3	0.1	0.3
4	4.9046	0.0011	4.9038	0.0014	4.9044	0.0015	0.5	0.2	0.3
5	4.9041	0.0010	4.9036	0.0012	4.9045	0.0013	0.3	0.2	0.5
6	4.9008	0.0013	4.8992	0.0010	4.9011	0.0012	1.0	0.2	1.2
7	4.9046	0.0029			4.9045	0.0015		0.0	
8	4.9025	0.0017	4.9061	0.0009	4.9029	0.0022	1.9	0.2	1.3
9	4.9028	0.0034	4.9026	0.0022	4.9024	0.0023	0.0	0.1	0.1
10	4.9044	0.0024	4.9039	0.0016	4.9045	0.0016	0.2	0.0	0.3
11	4.9020	0.0017	4.9019	0.0021	4.9020	0.0020	0.0	0.0	0.0
12	4.9027	0.0013	4.9028	0.0022	4.9030	0.0022	0.1	0.1	0.0
13	4.9026	0.0019	4.9027	0.0013	4.9026	0.0014	0.0	0.0	0.0
14	4.9026	0.0011	4.9026	0.0014	4.9028	0.0014	0.0	0.1	0.1
15	4.9042	0.0014							
16	4.9044	0.0009	4.9045	0.0016	4.9047	0.0016	0.1	0.2	0.1
17	4.9044	0.0020	4.9044	0.0018	4.9036	0.0019	0.0	0.3	0.3
18	4.9043	0.0021	4.9043	0.0013	4.9037	0.0013	0.0	0.2	0.3
19	4.9007	0.0011	4.9005	0.0011	4.9011	0.0011	0.1	0.3	0.4
20	4.9007	0.0010	4.9004	0.0011	4.9007	0.0012	0.2	0.0	0.2
21	4.9036	0.0026	4.9036	0.0019	4.9042	0.0018	0.0	0.2	0.2
22	4.9002	0.0011	4.9011	0.0011	4.9013	0.0010	0.6	0.7	0.1
23	4.9042	0.0019	4.9044	0.0013	4.9046	0.0013	0.1	0.2	0.1
24	4.9041	0.0011	4.9046	0.0016	4.9049	0.0016	0.3	0.4	0.1
25	4.9059	0.0028	4.9003	0.0011	4.9007	0.0012	1.8	1.7	0.2
26	4.9039	0.0013	4.9046	0.0019	4.9043	0.0019	0.3	0.2	0.1
27	4.9041	0.0012	4.9047	0.0018	4.9046	0.0019	0.3	0.3	0.0
28	4.9040	0.0008			4.9051	0.0014		0.6	
29	4.9011	0.0017	4.9020	0.0020	4.9024	0.0019	0.3	0.5	0.1
30	4.9023	0.0000	4.9025	0.0013	4.9031	0.0014	0.2	0.6	0.3

AVG		0.0016		0.0015		0.0016	0.3	0.3	0.3
MAX		0.0034		0.0022		0.0023	1.9	1.7	1.3
MIN		0.0000		0.0009		0.0010	0.0	0.0	0.0

2.3.3. Roundness R1 (un-filtered)

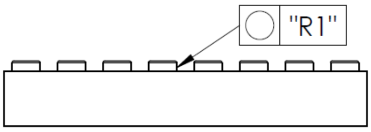


Table 11: Item 1 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 1, *R1*	1st round		2nd round		3rd round		2nd round versus 1st round	3rd round versus 1st round	3rd round versus 2nd round
ID no.	Y	U	Y	U	Y	U	|En| [-]	|En| [-]	|En| [-]
1	0.0039	0.0018	0.0041	0.0018	0.0041	0.0018	0.1	0.1	0.0
2	0.0037	0.0022	0.0044	0.0023	0.0040	0.0021	0.2	0.1	0.1
3	0.0034	0.0018	0.0034	0.0018	0.0039	0.0018	0.0	0.2	0.2
4	0.0038	0.0020	0.0037	0.0020	0.0040	0.0020	0.0	0.1	0.1
5	0.0051	0.0018	0.0050	0.0018	0.0047	0.0018	0.1	0.2	0.1
6	0.0035	0.0019	0.0044	0.0019	0.0035	0.0018	0.3	0.0	0.3
7	0.0037	0.0021			0.0041	0.0020		0.2	
8	0.0046	0.0027	0.0051	0.0021	0.0056	0.0026	0.2	0.3	0.1
9	0.0040	0.0018	0.0041	0.0018	0.0041	0.0019	0.0	0.0	0.0
10	0.0071	0.0046	0.0035	0.0018	0.0037	0.0018	0.7	0.7	0.1
11	0.0040	0.0032	0.0042	0.0020	0.0046	0.0020	0.1	0.2	0.1
12	0.0048	0.0022	0.0042	0.0019	0.0043	0.0018	0.2	0.2	0.0
13	0.0035	0.0018	0.0032	0.0018	0.0038	0.0018	0.1	0.1	0.2
14	0.0036	0.0018	0.0033	0.0018	0.0033	0.0018	0.1	0.1	0.0
15	0.0034	0.0018							
16	0.0047	0.0024	0.0034	0.0018	0.0036	0.0018	0.4	0.4	0.1
17	0.0045	0.0019	0.0044	0.0018	0.0059	0.0018	0.0	0.5	0.6
18	0.0072	0.0027	0.0059	0.0019	0.0055	0.0021	0.4	0.5	0.1
19	0.0051	0.0025	0.0034	0.0021	0.0041	0.0019	0.5	0.3	0.2
20	0.0035	0.0019	0.0035	0.0020	0.0041	0.0020	0.0	0.2	0.2
21	0.0050	0.0018	0.0051	0.0018	0.0050	0.0018	0.1	0.0	0.0
22	0.0039	0.0019	0.0034	0.0039	0.0034	0.0037	0.1	0.1	0.0
23	0.0050	0.0018	0.0051	0.0018	0.0049	0.0018	0.0	0.0	0.1
24	0.0035	0.0018	0.0036	0.0018	0.0037	0.0018	0.0	0.1	0.0
25	0.0046	0.0023	0.0040	0.0019	0.0039	0.0019	0.2	0.2	0.0
26	0.0048	0.0018	0.0044	0.0018	0.0052	0.0018	0.2	0.2	0.3
27	0.0045	0.0018	0.0045	0.0018	0.0044	0.0018	0.0	0.0	0.0
28	0.0037	0.0019			0.0040	0.0020		0.1	
29	0.0039	0.0019	0.0042	0.0020	0.0042	0.0019	0.1	0.1	0.0
30	0.0070	0.0021	0.0034	0.0018	0.0032	0.0018	1.3	1.4	0.1

AVG		0.0021		0.0020		0.0020	0.2	0.2	0.1
MAX		0.0046		0.0039		0.0037	1.3	1.4	0.6
MIN		0.0018		0.0018		0.0018	0.0	0.0	0.0

2.3.4. Roundness R1 (filter Gauss 150)

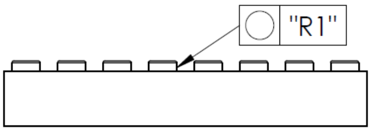


Table 12: Item 1 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 1, *R1*	1st round		2nd round		3rd round		2nd round versus 1st round	3rd round versus 1st round	3rd round versus 2nd round
ID no.	Y	U	Y	U	Y	U	|En| [-]	|En| [-]	|En| [-]
1	0.0034	0.0018	0.0035	0.0018	0.0035	0.0018	0.0	0.0	0.0
2	0.0030	0.0022	0.0037	0.0023	0.0034	0.0021	0.2	0.1	0.1
3	0.0029	0.0018	0.0027	0.0018	0.0034	0.0018	0.1	0.2	0.3
4	0.0027	0.0020	0.0030	0.0020	0.0034	0.0020	0.1	0.2	0.1
5	0.0042	0.0018	0.0042	0.0018	0.0042	0.0018	0.0	0.0	0.0
6	0.0030	0.0019	0.0040	0.0019	0.0030	0.0018	0.4	0.0	0.4
7	0.0030	0.0021			0.0035	0.0020		0.2	
8	0.0040	0.0027	0.0047	0.0021	0.0048	0.0026	0.2	0.2	0.0
9	0.0035	0.0018	0.0035	0.0018	0.0036	0.0019	0.0	0.0	0.1
10	0.0066	0.0046	0.0032	0.0018	0.0031	0.0018	0.7	0.7	0.0
11	0.0036	0.0032	0.0036	0.0020	0.0039	0.0020	0.0	0.1	0.1
12	0.0041	0.0022	0.0034	0.0019	0.0035	0.0018	0.2	0.2	0.0
13	0.0029	0.0018	0.0028	0.0018	0.0030	0.0018	0.0	0.1	0.1
14	0.0030	0.0018	0.0028	0.0018	0.0030	0.0018	0.1	0.0	0.1
15	0.0030	0.0018							
16	0.0043	0.0024	0.0030	0.0018	0.0030	0.0018	0.4	0.4	0.0
17	0.0039	0.0019	0.0039	0.0018	0.0054	0.0018	0.0	0.6	0.6
18	0.0062	0.0027	0.0048	0.0019	0.0047	0.0021	0.4	0.4	0.0
19	0.0042	0.0025	0.0030	0.0021	0.0033	0.0019	0.4	0.3	0.1
20	0.0030	0.0019	0.0031	0.0020	0.0035	0.0020	0.0	0.2	0.1
21	0.0045	0.0018	0.0047	0.0018	0.0047	0.0018	0.1	0.1	0.0
22	0.0035	0.0019	0.0029	0.0039	0.0030	0.0037	0.1	0.1	0.0
23	0.0042	0.0018	0.0043	0.0018	0.0043	0.0018	0.0	0.0	0.0
24	0.0031	0.0018	0.0030	0.0018	0.0031	0.0018	0.0	0.0	0.0
25	0.0040	0.0023	0.0035	0.0019	0.0034	0.0019	0.2	0.2	0.0
26	0.0043	0.0018	0.0039	0.0018	0.0048	0.0018	0.2	0.2	0.4
27	0.0040	0.0018	0.0040	0.0018	0.0041	0.0018	0.0	0.0	0.0
28	0.0030	0.0019			0.0031	0.0020		0.1	
29	0.0034	0.0019	0.0038	0.0020	0.0036	0.0019	0.1	0.1	0.1
30	0.0037	0.0021	0.0030	0.0018	0.0027	0.0018	0.2	0.4	0.1

AVG		0.0021		0.0020		0.0020	0.2	0.2	0.1
MAX		0.0046		0.0039		0.0037	0.7	0.7	0.6
MIN		0.0018		0.0018		0.0018	0.0	0.0	0.0

2.3.5. Length L1

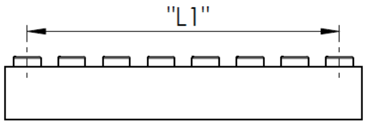


Table 13: Item 1 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 1, *L1*	1st round		2nd round		3rd round		2nd round versus 1st round	3rd round versus 1st round	3rd round versus 2nd round
ID no.	Y	U	Y	U	Y	U	|En| [-]	|En| [-]	|En| [-]
1	55.9218	0.0054	55.9056	0.0055	55.9128	0.0053	2.1	1.2	0.9
2	55.9560	0.0054	55.9453	0.0055	55.9532	0.0053	1.4	0.4	1.0
3	55.9494	0.0053	55.9365	0.0055	55.9451	0.0053	1.7	0.6	1.1
4	55.9545	0.0053	55.9421	0.0055	55.9488	0.0053	1.6	0.8	0.9
5	55.9555	0.0054	55.9462	0.0055	55.9538	0.0053	1.2	0.2	1.0
6	55.9624	0.0054	55.9449	0.0055	55.9519	0.0054	2.3	1.4	0.9
7	55.9526	0.0054			55.9552	0.0053		0.3	
8	55.9171	0.0054	55.9034	0.0055	55.9137	0.0053	1.8	0.5	1.3
9	55.9236	0.0054	55.9130	0.0055	55.9139	0.0053	1.4	1.3	0.1
10	55.9587	0.0054	55.9508	0.0055	55.9559	0.0053	1.0	0.4	0.7
11	55.9496	0.0053	55.9421	0.0055	55.9449	0.0053	1.0	0.6	0.4
12	55.9196	0.0054	55.9096	0.0055	55.9111	0.0053	1.3	1.1	0.2
13	55.9496	0.0054	55.9513	0.0055	55.9468	0.0053	0.2	0.4	0.6
14	55.9537	0.0053	55.9449	0.0055	55.9443	0.0053	1.1	1.3	0.1
15	55.9573	0.0054							
16	55.9606	0.0054	55.9605	0.0055	55.9585	0.0053	0.0	0.3	0.3
17	55.9518	0.0054	55.9526	0.0055	55.9489	0.0053	0.1	0.4	0.5
18	55.9544	0.0053	55.9532	0.0055	55.9527	0.0053	0.1	0.2	0.1
19	55.9551	0.0054	55.9482	0.0055	55.9541	0.0054	0.9	0.1	0.8
20	55.9549	0.0054	55.9498	0.0055	55.9528	0.0054	0.7	0.3	0.4
21	55.9481	0.0053	55.9467	0.0055	55.9476	0.0053	0.2	0.1	0.1
22	55.9537	0.0054	55.9540	0.0056	55.9553	0.0054	0.0	0.2	0.2
23	55.9545	0.0053	55.9509	0.0055	55.9533	0.0053	0.5	0.2	0.3
24	55.9607	0.0054	55.9606	0.0055	55.9591	0.0053	0.0	0.2	0.2
25	55.9550	0.0054	55.9523	0.0056	55.9517	0.0054	0.4	0.4	0.1
26	55.9480	0.0054	55.9508	0.0055	55.9490	0.0053	0.4	0.1	0.2
27	55.9537	0.0054	55.9490	0.0055	55.9496	0.0053	0.6	0.5	0.1
28	55.9452	0.0053			55.9513	0.0053		0.8	
29	55.9345	0.0054	55.9458	0.0055	55.9444	0.0053	1.5	1.3	0.2
30	55.9471	0.0054	55.9430	0.0055	55.9463	0.0053	0.5	0.1	0.4

AVG		0.0054		0.0055		0.0053	0.9	0.5	0.5
MAX		0.0054		0.0056		0.0054	2.3	1.4	1.3
MIN		0.0053		0.0055		0.0053	0.0	0.1	0.1

2.4. Analysis of reference measurements

The variation of the reference measurements can be used to evaluate repeatability and consistency of measurements [Hansen et al., 1996] [De Chiffre et al., 2004]. But no repeated measurements are performed for the 30 samples. Instead the repeatability was evaluated based on one single sample with 5 repeated measurements.

The measurements for the reference values before the circulation are given in Figure 12 for all the measurands. Notice that the deviation of each measurement is based on the deviation between the measured value and the average value of the measurements. The variations do not exceed 2.5 µm for all the measurands.

Form plots of the roundness *R1* for Item 1 ID no. 2 are shown in Figure 13 (un-filtered) and Figure 14 (filter Gauss 150). It is clear from the form plots, that they are very similar like finger prints, although they have been measured in three different time sequences.

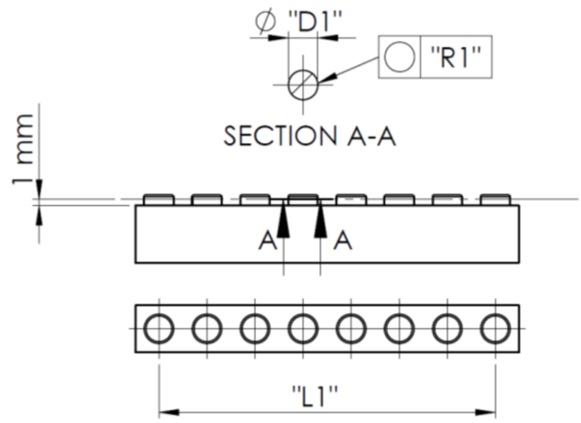


Figure 11: Item 1 – Overview of measurands; D1, R1 and L1.

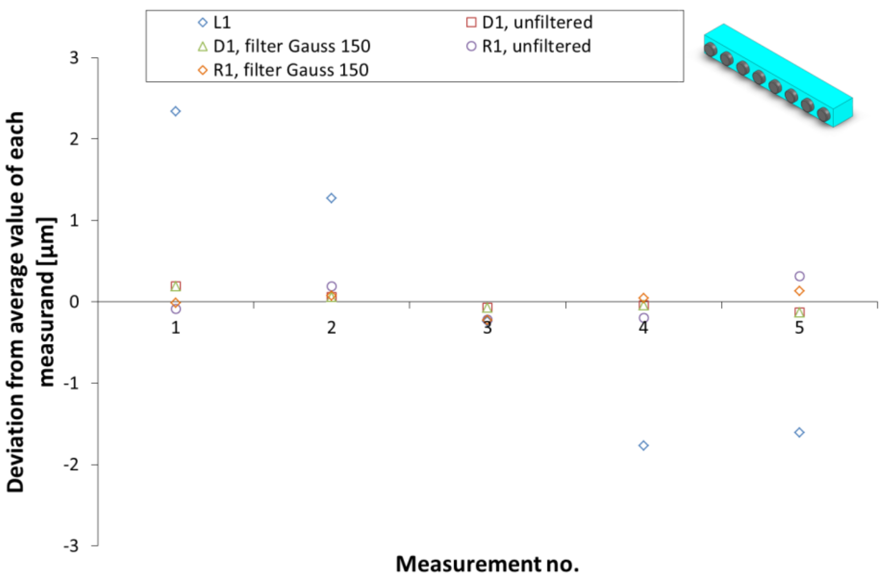


Figure 12: Item 1 - Variation of five repeated measurements on Item 1, before circulation.

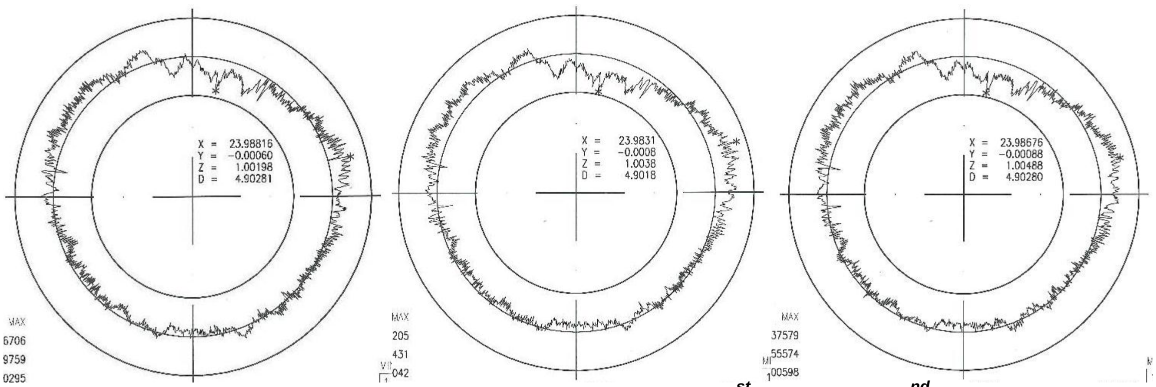


Figure 13: Item 1 ID no. 2 – Form of the roundness R1 (un-filtered), 1st round (left), 2nd round (middle), and 3rd round (right).

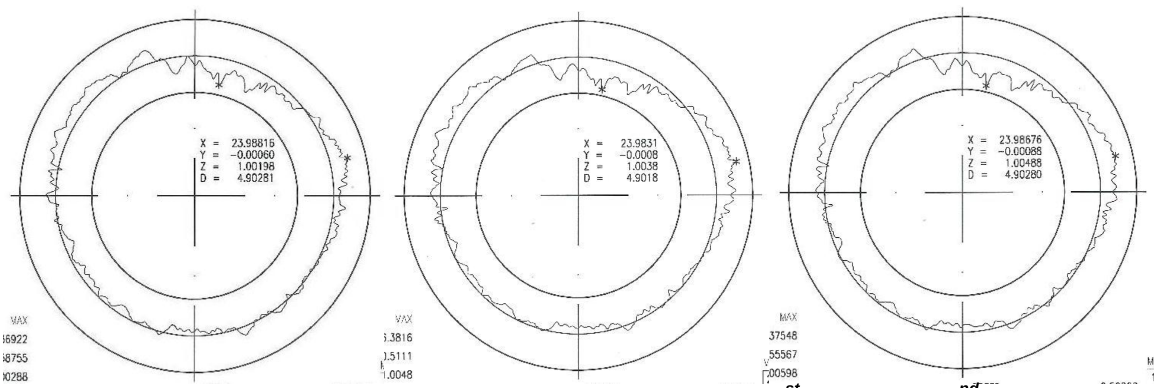


Figure 14: Item 1 ID no. 2 – Form of the roundness R1 (filter Gauss 150), 1st round (left), 2nd round (middle), and 3rd round (right).

2.5. Comparison of values after circulation with reference values before circulation

Due to a cooling compressor breakdown in the laboratory, some temperature problems were detected (see Figure 15 and Figure 16) during the 2nd round after circulation, in connection with measurements on Item 1. New reference measurements were thus performed at CGM (3rd round). A histogram of all the E_n values between 3rd and 2nd round is shown in Figure 17. NPL has supported with CMM measurements for the length *L1* using their Zeiss F25 micro-CMM for nine LEGO bricks (with the ID numbers 1-6 and 8-10). The data from NPL were based on the average of 5 repeated measurements with a general expanded uncertainty of 0.37 µm ($k = 2$).

Values by CGM for the length *L1* on Item 1 are compared with values by NPL (F25) in Figure 18 and Table 14. These measurements confirmed the measurements performed by CGM. It is difficult to conclude from the measurements whether the dimensions of LEGO bricks have systematically changed over time or not.

For Item 1, reference values are estimated based on the average values of the three measurement rounds, when all dataset are available. For Item 1, the uncertainty for each ID is assumed to be the maximum uncertainty through the three measurement rounds.

The calculated reference values and their corresponding uncertainties are shown in Table 15.

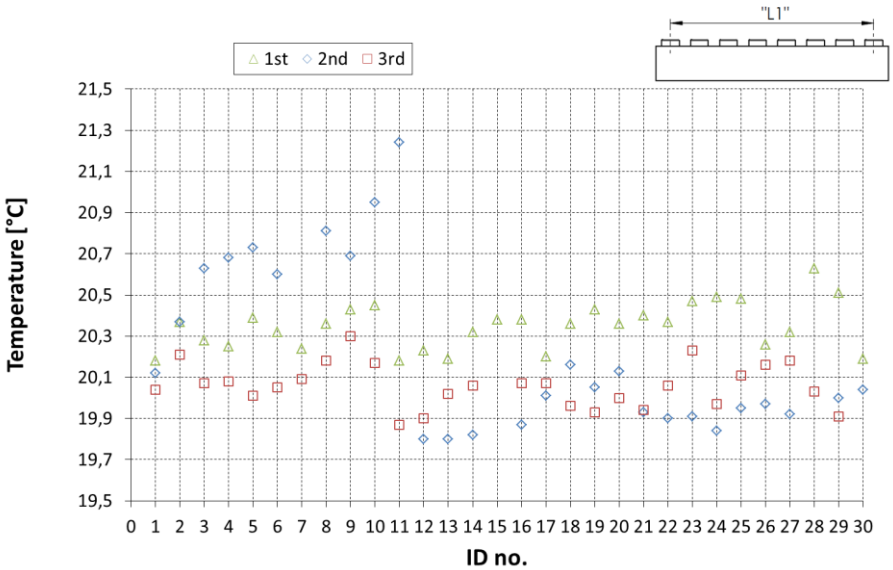


Figure 15: Temperature of Item 1 in the three measurement rounds.

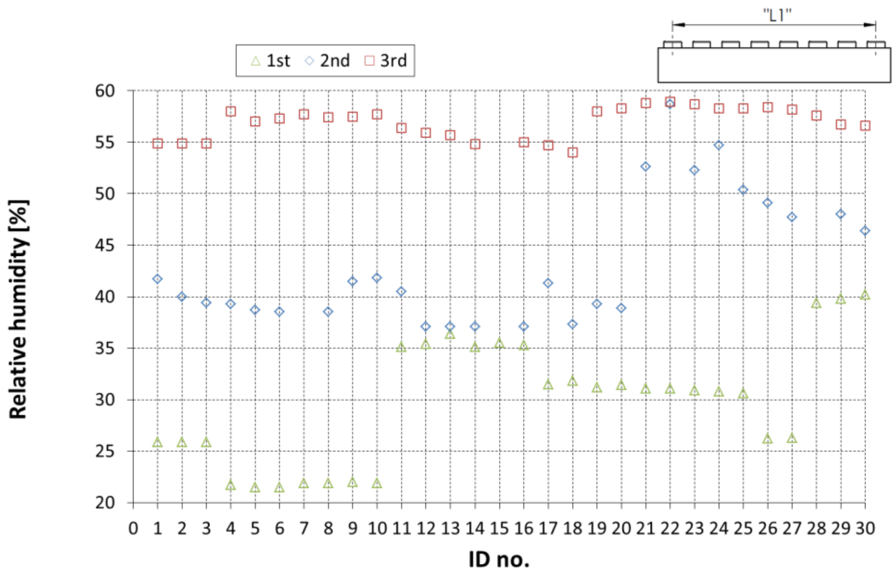


Figure 16: Relative humidity for Item 1 in the three measurement rounds.

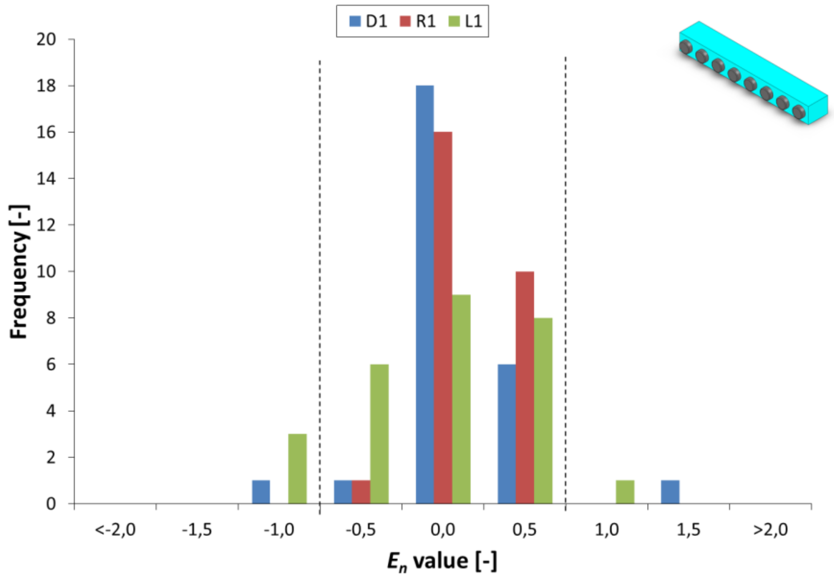


Figure 17: Item 1 – Histogram of E_n values between 3rd and 2nd round for all measurands.

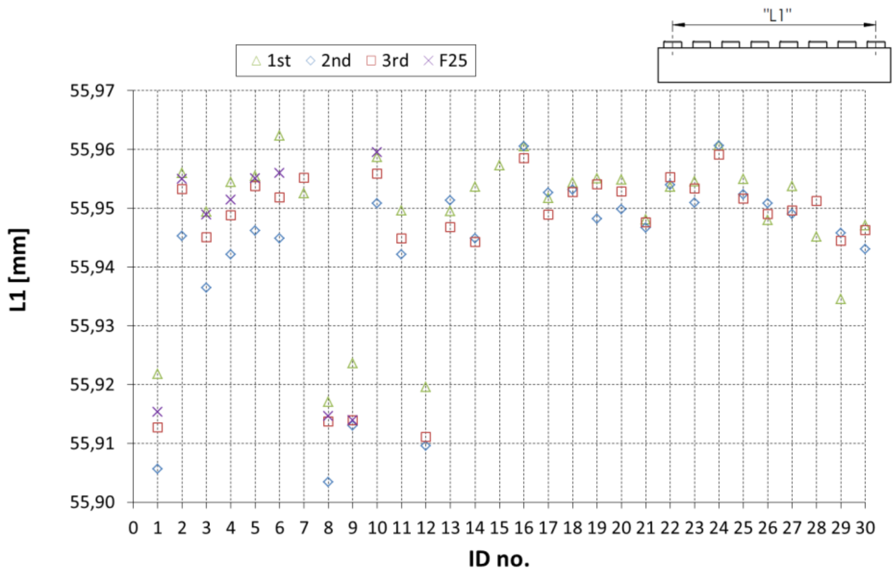


Figure 18: Length L1 for Item 1 in the three measurement rounds. NPL's results are included in the case for L1 (using F25).

Table 14: Values by CGM for the length L1 on Item 1 compared with values by NPL (F25) and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 1, *L1*	3rd round		AVG		F25		3rd round versus F25	AVG versus F25
ID no.	Y	U	Y	U	Y	U	|En| [-]	|En| [-]
1	55.9128	0.0055	55.9134	0.0055	55.9153	0.0004	0.5	0.3
2	55.9532	0.0055	55.9515	0.0055	55.9550	0.0004	0.3	0.6
3	55.9451	0.0055	55.9437	0.0055	55.9489	0.0004	0.7	0.9
4	55.9488	0.0055	55.9484	0.0055	55.9515	0.0004	0.5	0.6
5	55.9538	0.0055	55.9518	0.0055	55.9551	0.0004	0.2	0.6
6	55.9519	0.0055	55.9530	0.0055	55.9559	0.0004	0.7	0.5
7								
8	55.9137	0.0055	55.9114	0.0055	55.9146	0.0004	0.2	0.6
9	55.9139	0.0055	55.9168	0.0055	55.9139	0.0004	0.0	0.5
10	55.9559	0.0055	55.9551	0.0055	55.9596	0.0004	0.7	0.8

AVG		0.0055		0.0055		0.0004	0.4	0.6
MAX		0.0055		0.0055		0.0004	0.7	0.9
MIN		0.0055		0.0055		0.0004	0.0	0.3

Table 15: Item 1 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

	Diameter *D1*		Roundness *R1*		Length *L1*	
ID no.	Y	U	Y	U	Y	U
1	4.9026	0.0022	0.0040	0.0018	55.9134	0.0055
2	4.9043	0.0015	0.0040	0.0023	55.9515	0.0055
3	4.9024	0.0014	0.0035	0.0018	55.9437	0.0055
4	4.9043	0.0015	0.0038	0.0020	55.9484	0.0055
5	4.9041	0.0013	0.0050	0.0018	55.9518	0.0055
6	4.9004	0.0012	0.0038	0.0019	55.9530	0.0055
7	4.9045	0.0015	0.0039	0.0021	55.9539	0.0054
8	4.9038	0.0023	0.0051	0.0027	55.9114	0.0055
9	4.9026	0.0023	0.0041	0.0019	55.9168	0.0055
10	4.9043	0.0016	0.0048	0.0046	55.9551	0.0055
11	4.9020	0.0021	0.0043	0.0032	55.9455	0.0055
12	4.9028	0.0023	0.0044	0.0022	55.9134	0.0055
13	4.9027	0.0014	0.0035	0.0018	55.9492	0.0055
14	4.9027	0.0014	0.0034	0.0018	55.9476	0.0055
15	4.9042	0.0015	0.0034	0.0018	55.9573	0.0054
16	4.9046	0.0016	0.0039	0.0024	55.9599	0.0055
17	4.9041	0.0019	0.0049	0.0019	55.9511	0.0055
18	4.9041	0.0014	0.0062	0.0027	55.9534	0.0055
19	4.9008	0.0011	0.0042	0.0025	55.9524	0.0055
20	4.9006	0.0012	0.0037	0.0020	55.9525	0.0055
21	4.9038	0.0019	0.0050	0.0018	55.9475	0.0055
22	4.9009	0.0011	0.0036	0.0039	55.9543	0.0056
23	4.9044	0.0013	0.0050	0.0018	55.9529	0.0055
24	4.9045	0.0016	0.0036	0.0018	55.9601	0.0055
25	4.9023	0.0012	0.0042	0.0023	55.9530	0.0056
26	4.9043	0.0019	0.0048	0.0018	55.9493	0.0055
27	4.9045	0.0019	0.0045	0.0018	55.9508	0.0055
28	4.9045	0.0015	0.0038	0.0020	55.9482	0.0053
29	4.9019	0.0020	0.0041	0.0020	55.9416	0.0055
30	4.9026	0.0014	0.0045	0.0021	55.9455	0.0055
AVG		0.0016		0.0022		0.0055
MAX		0.0023		0.0046		0.0056
MIN		0.0011		0.0018		0.0053

2.6. Conclusion

The coordinate measuring machine used at CGM to measure Item 1 is a mechanical CMM equipped with a static probe. The CMM is of the type Zeiss UPMC 850 CARAT. The CMM is placed in a temperature controlled room (T = 20 °C ± 0.4 °C and a maximum of 60 % RH).

The PUMA approach [ISO 14253-2, 2011] is used for uncertainty estimation, which is a simplification of GUM approach [ISO/IEC Guide 98-3, 2008].

The variations did not exceed 2.5 µm for the repeated measurements.

In order to judge the agreement between measurements through time, the E_n value normalised with respect to the stated uncertainty was computed according to ISO 17043 guidelines [ISO/IEC 17043, 2010]. If $|E_n| < 1$ the quality of the measurement result is acceptable, while it is not acceptable if $|E_n| \geq 1$.

Reference measurements were carried out by CGM, before circulation, 1st round (December 2012 – May 2013). These values were verified by new measurements after circulation, 2nd round (May 2013 – June 2013). Due to a cooling compressor breakdown in the laboratory, some temperature problems were detected during the 2nd round after circulation, in connection with measurements on Item 1. New reference measurements were thus performed at CGM (3rd round). NPL has supported with CMM measurements for the length *L1* using their Zeiss F25 micro-CMM for nine LEGO bricks (with the ID numbers 1-6 and 8-10). The data from NPL were based on the average of 5 repeated measurements with a general expanded uncertainty of 0.37 µm ($k = 2$). These measurements confirmed that the measurements performed by CGM were in the accepted range.

For Item 1, reference values are estimated based on the average values of the three measurement rounds, when all dataset are available. For Item 1, the uncertainty for each ID is assumed to be the maximum uncertainty through the three measurement rounds.

Expanded measurement uncertainties obtained by CGM were in the range of 1.6-5.5 µm for the plastic part.

3. Reference measurements Item 2

The reference measurements are divided in following subcategories; Measuring conditions, Data processing, Reference values, Analysis of reference measurement data, Comparison of values after circulation with reference values before circulation, and Conclusion.

3.1. Measuring conditions

The measuring conditions are divided in five subcategories; Equipment, Traceability, Used software, Dates of measurements, and Measurement procedure.

3.1.1. Equipment

The coordinate measuring machine used at CGM to measure the 29 sets of Item 2 is a mechanical CMM equipped with a dynamic probe. The CMM is of the type Zeiss OMC 850 (Figure 19), where some of its specifications can be seen in Table 16. The CMM is placed in a temperature controlled room (T = 20 °C ± 1.0 °C and a maximum of 60 % RH).

Figure 19: CMM of the type Zeiss OMC 850 placed at CGM.

Table 16: Some selected features for Zeiss OMC 850.

Features for Zeiss OMC 850	
Measuring volume	(x, y, z) = 820mm x 590mm x 470mm
MPE	One-dimensional length measuring uncertainty: u1 = (2.5 + L / 300) µm Three-dimensional length measuring uncertainty: u3 = 3+L/250µm (L in mm)

3.1.2. Traceability

The used equipment and reference artifacts to generate traceability are shown in Table 17. A grade I steel block and a ring gauge, was used as length and diameter/roundness references respectively.

Table 17: Used equipment and reference artifacts to generate traceability.

Object	Certificate
Ring gauge, Ø8 mm	Unimerco Certificate 353-155696 Dated: 19th February 2013
Grade I steel blocks, 50 mm	Unimerco Certificate 353-155697 Dated: 21st February 2013
Humidity and Temperature Datalogger RHT20	Product datasheet and user's manual can be acquired from http://www.extech.com/instruments/product.asp?catid=37&prodid=529 Dated: 16th April 2013 Data logger is tested against Risø certificate of calibration Risø Certificate 21575 Dated: 18th January 2011
Calibration of Zeiss OMC 850	Brock & Michelsen Certificate S017156 Dated: 21st June 2011

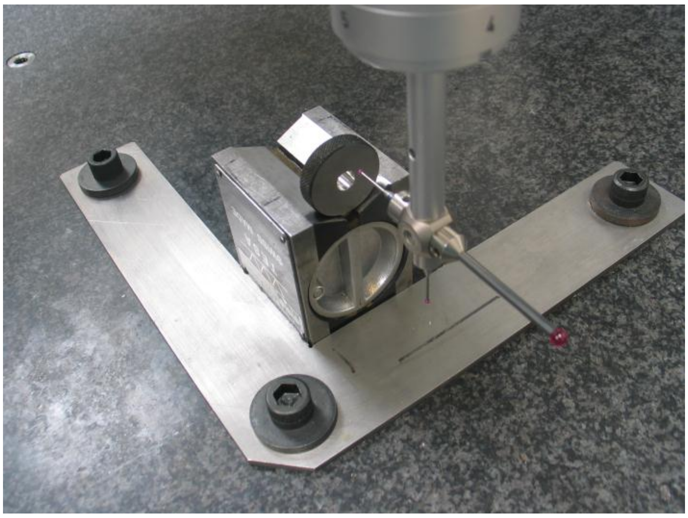


Figure 20: Ring gauge, Ø8 mm.

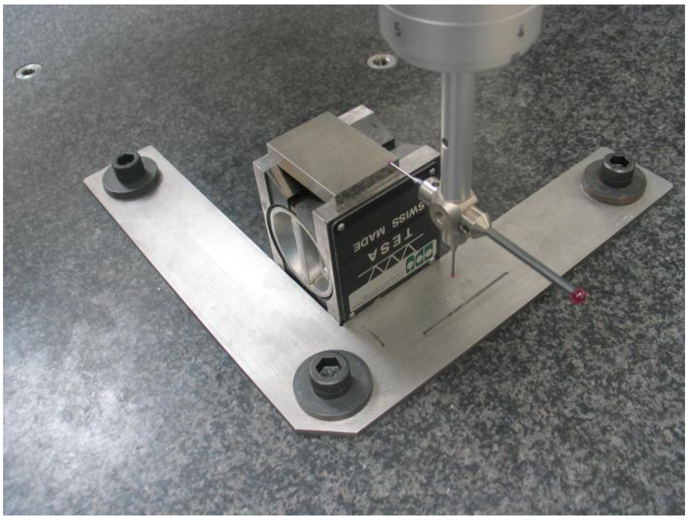


Figure 21: Grade I steel blocks, 50 mm.

3.1.3. Used software

The used software is shown in Table 18.

Table 18: Used software.

Software
Calypso version 5.0

3.1.4. Dates of measurements

Reference measurements were carried out by CGM, before circulation. These values were verified by new measurements after circulation, as indicated in Table 19.

Table 19: Dates of measurements at CGM.

Item 2	Month	Year
Measured at CGM before circulation	December	2012
	January	2013
	March	2013
Measured at CGM after circulation	February	2013
	March	2013
	May	2013
	August	2013

3.1.5. Measurement procedure

The presentation of Item 2, measurements details, datums to be used and measurands can be found in [Technical Protocol], and is summarized in Table 20 and Figure 22. The selected geometrical features were length, diameter and roundness. An example on the applied measurement protocol can be found in Appendix based on a transcript from the CMM software. Diameter and roundness measurements are based on 24 points and no filter is applied.

Five repeated measurements and transfer of traceability by comparator measurement were carried out for the 29 samples. The measurement set-up is illustrated in (Figure 23). Two different dynamic probes with Ø 2.0 mm and Ø 5.0 mm was used for the measurements.

The location of the temperature sensor is shown in Figure 24. Maximum temperature between machine and workpiece is assumed to be neglected because of acclimatisation. The 29 samples were acclimated in one week. It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The temperature was registered before and after each measurement.

The 29 samples were handled using gloves, handled by authorised personnel and treated in order to prevent damages. The 29 samples were cleaned gently using a soft brush. Additionally, the use of de-greasing liquid is also allowed. The 29 samples have been glued in connection with the fixture for the reference measurements. Datasheets for the applied glue from the supplier can be found in Appendix.

Table 20: Item 2 – Overview of measurands; D1, R1, D2, R2 and L1 [Technical Protocol].

Identification		Description
Diameter,	*D1*	Internal diameter, least square fitting (GG) *D1* – circle is measured 2 mm from datum B
Roundness,	*R1*	Roundness of internal diameter *R1* – on circle (LSCI) is measured 2 mm from datum B
Diameter,	*D2*	Internal diameter , least square fitting (GG) *D2* – circle is measured 12 mm from datum B
Roundness,	*R2*	Roundness of internal diameter *R2* – on circle (LSCI) is measured 12 mm from datum B
Length,	*L1*	Total length L1 - The length between the two “GG” planes, in the axis of the primary alignment (in the centre axis of the item – intersection between axis and planes)

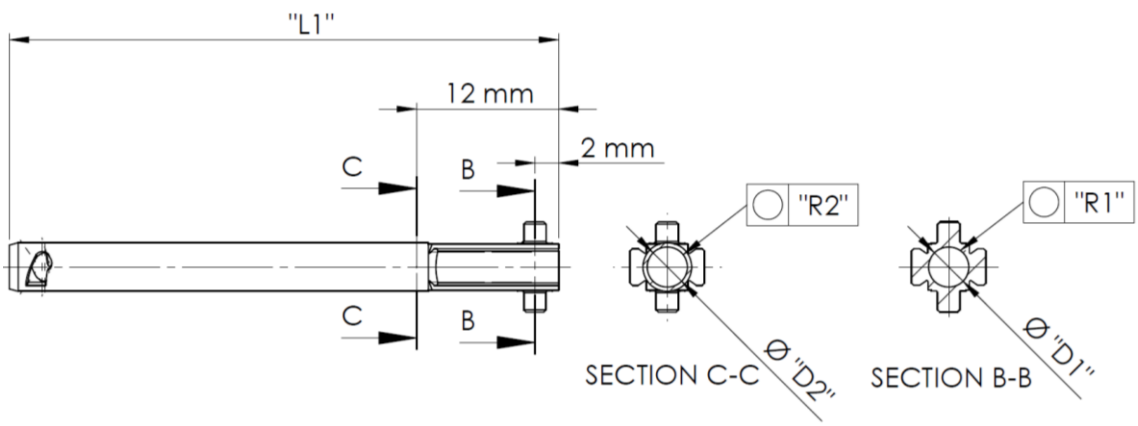


Figure 22: Item 2 – Overview of measurands; D1, R1, D2, R2 and L1.

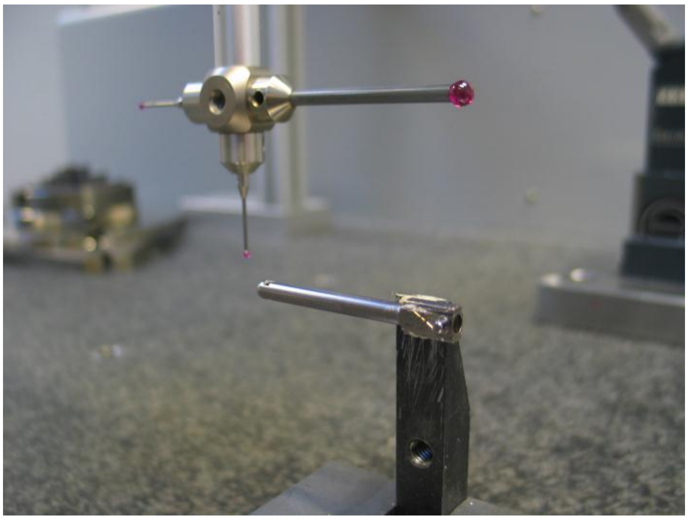


Figure 23: Measurement set-up for the 29 sets of Item 2.

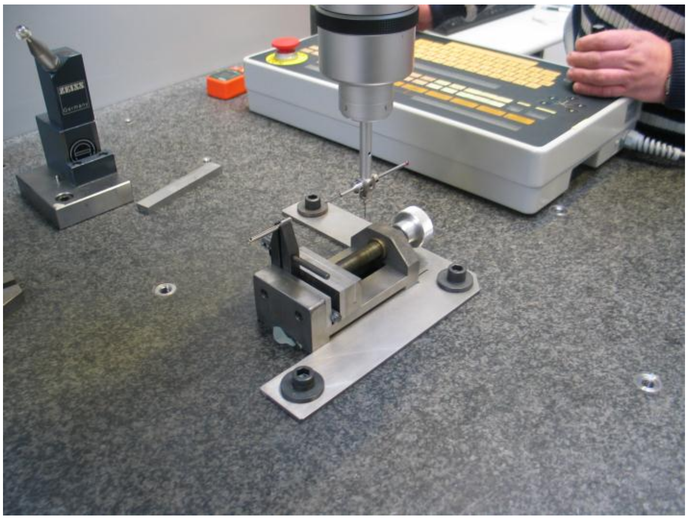


Figure 24: Location of temperature sensor. The temperature sensor is placed next to the controller on the right from the view of the operator.

3.2. Data processing

Data processing was divided in four subcategories; Uncorrected measurement results, Systematic errors, Measurement uncertainty, and Summarized bias and uncertainty budgets.

3.2.1. Uncorrected measurement results

The complete measurements including systematic error and uncertainty can be written as given in Equation 6.

$$Y = \overline{Y} - b \pm U(Y) \tag{6}$$

Here, Y is the final result, $\overline{Y}$ the average from repeated measurements, b the total bias (systematic error) and $U(Y)$ is the uncertainty.

An uncorrected measurement example for Item 2 ID no. 2 before circulation is given in Appendix for the five measurands; the diameter *D1*, the roundness *R1*, the diameter *D2*, the roundness *R2* and the length *L1*. Furthermore the uncorrected data for the reference artifacts are shown in Appendix too.

3.2.2. Systematic errors

The total systematic error can be written as the summation of all the systematic errors as given in Equation 7.

$$b = \sum_{i=1}^{n} b_i \tag{7}$$

For estimation of the systematic errors, the following components in Table 21 are included in the systematic error for Item 2. Furthermore it is indicated with a X which systematic errors, which are considered for each given measurand for Item 2. Regarding to the compensation of systematic deviation due to the force, it is normally recommended compensating for deflection of the styli and deflection of the sample. But there were no access for make this experiment, because the probe is dynamic, so this compensation is not implemented in the calculations. For the cases of roundness it is assumed that the compensation coming from expansion coefficient can be neglected.

Table 21: List of the systematic errors for the measuring of the reference measurements at CGM.

No.	Category	Symbol	Involved uncertainty contributions	Measurand				
				D1	***R1***	***D2***	***R2***	***L1***
1	Reference standard	$b_{r(1)}$	Compensation of systematic deviation due to reference artifact (ring gauge, Ø8 mm)	X		X		
		$b_{r(2)}$	Compensation of systematic deviation due to reference artifact (gauge block, 50 mm)					X
2	Environment	$b_{e(1)}$	Compensation of systematic deviation due to temperature (ring gauge, Ø8 mm)	X		X		
		$b_{e(2)}$	Compensation of systematic deviation due to temperature (gauge block, 50 mm)					X
		$b_{e(3)}$	Compensation of systematic deviation due to temperature (work piece)	X		X		X

A bias budget example is given for Item 2 ID no. 2 before circulation in Appendix.

3.2.3. Measurement uncertainty

The PUMA approach [ISO 14253-2, 2011] is used, which is a simplification of GUM approach [ISO/IEC Guide 98-3, 2008]. Equations 8 and 9 are used.

$$U = k \cdot u_c \qquad (k = 2) \tag{8}$$

Here, U is the expanded uncertainty, u_c is the combined standard uncertainty and k is the coverage factor ($k = 2$ for a coverage probability of 95 %). The considered uncertainty contributors are given in Equation 9.

$$U = k \cdot \sqrt{u_r^2 + u_{rep}^2 + u_w^2 + u_{e(1)}^2 + u_{e(2)}^2 + u_{e(3)}^2 + u_{e(4)}^2 + u_p^2} \tag{9}$$

The following components from Equation 9 are described in Table 22 and included in the budget for Item 2. Note that the uncertainty components are divided in two categories: type A and type B. Furthermore it is indicated with a X which uncertainty contributions, which are considered for each given measurand for Item 2. For the cases of roundness it is assumed that the compensation coming from expansion coefficient can be neglected.

Table 22: List of the uncertainty contributors for the measuring uncertainty budget of the reference measurements at CGM.

No.	Category	Symbol	Involved uncertainty contributions	Type	Measurand				
					D1	***R1***	***D2***	***R2***	***L1***
1	Reference standard	$u_{r(1)}$	Uncertainty component from ring gauge, Ø8 mm	B	X	X	X	X	
		$u_{r(2)}$	Uncertainty component from gauge block, 50 mm	B					X
2	Measuring instrument	$u_{rep(1)}$	Uncertainty component from repeatability on ring gauge, Ø8 mm	A	X	X	X	X	
		$u_{rep(2)}$	Uncertainty component from repeatability on gauge block, 50 mm	A					X
3	Workpiece	u_w	Uncertainty component from work piece	B	X	X	X	X	X
4	Environment	$u_{e(1)}$	Uncertainty component from temperature difference between workpiece and instrument	B	X		X		X
		$u_{e(2)}$	Uncertainty component from temperature deviation from standard reference temperature for instrument	B	X		X		X
		$u_{e(3)}$	Uncertainty component from temperature deviation from standard reference temperature for workpiece	B	X		X		X
		$u_{e(4)}$	Uncertainty component from workpiece expansion coefficient uncertainty	B	X		X		X
5	Procedure	u_p	Uncertainty component from measurement process	A	X	X	X	X	X

An uncertainty budget example is given for Item 2 ID no. 2 before circulation in Appendix.

The graphs in Figure 25, Figure 26, Figure 27, Figure 28 and Figure 29 give a sense of the distribution of the uncertainty components for Item 2 ID no. 2.

In Figure 25 and Figure 27 it is clear that uncertainty component from ring gauge ($u_{r(1)}$), uncertainty component from repeatability on ring gauge ($u_{rep(1)}$), uncertainty component from work piece (u_w)

and uncertainty component from measurement process (u_p) are significant for *D1* and *D2* for Item 2 ID no. 2, because their contribution exceeds the limit of significance of 10% from the sum of all uncertainty components.

In Figure 26 and Figure 28 it is clear that uncertainty component from repeatability on ring gauge ($u_{rep(1)}$), uncertainty component from work piece (u_w) and uncertainty component from measurement process (u_p) are significant for *R1* and *R2* for Item 2 ID no. 2, because their contribution exceeds the limit of significance of 10% from the sum of all uncertainty components.

In Figure 29 it is clear that uncertainty component from work piece (u_w) and uncertainty component from measurement process (u_p) are significant for *L1* for Item 2 ID no. 2, because their contribution exceeds the limit of significance of 10% from the sum of all uncertainty components.

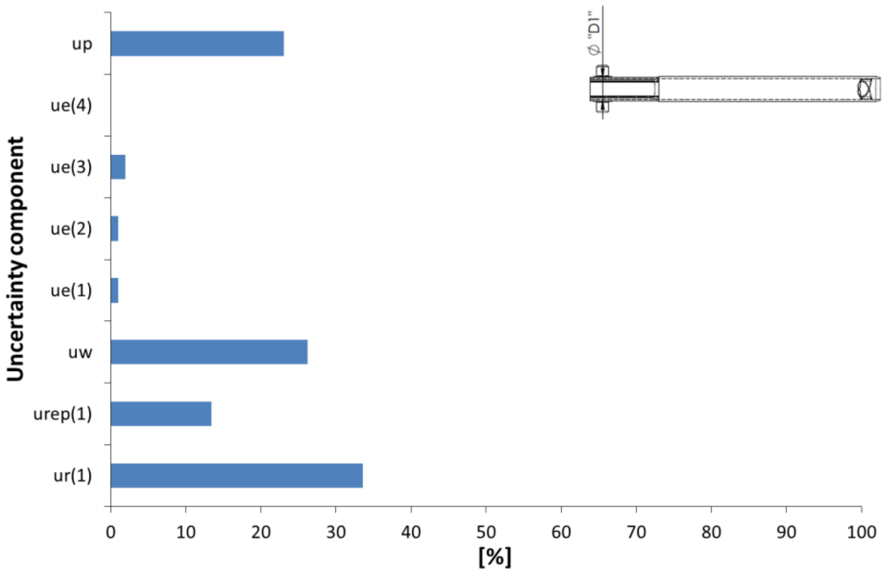


Figure 25: Item 2, ID no. 2, diameter D1, Distribution of uncertainty components.

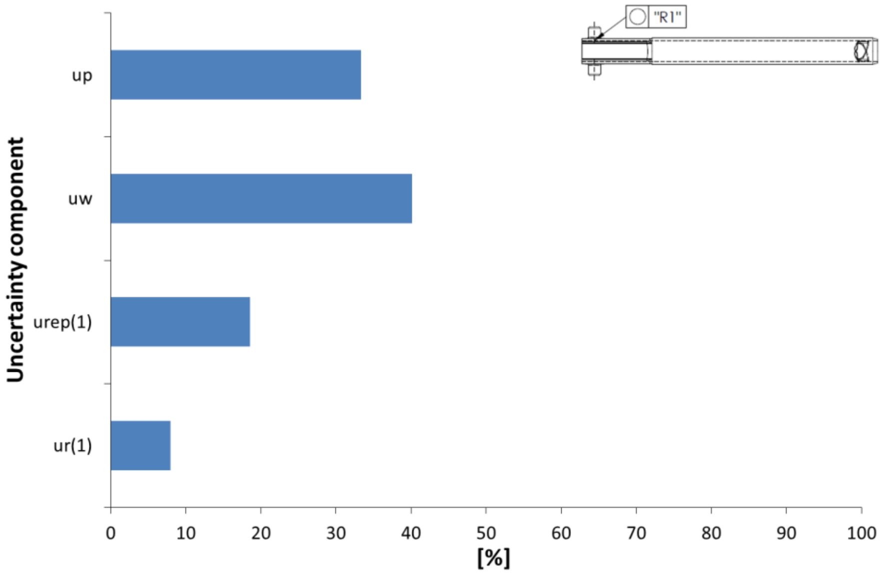


Figure 26: Item 2, ID no. 2, roundness R1, Distribution of uncertainty components.

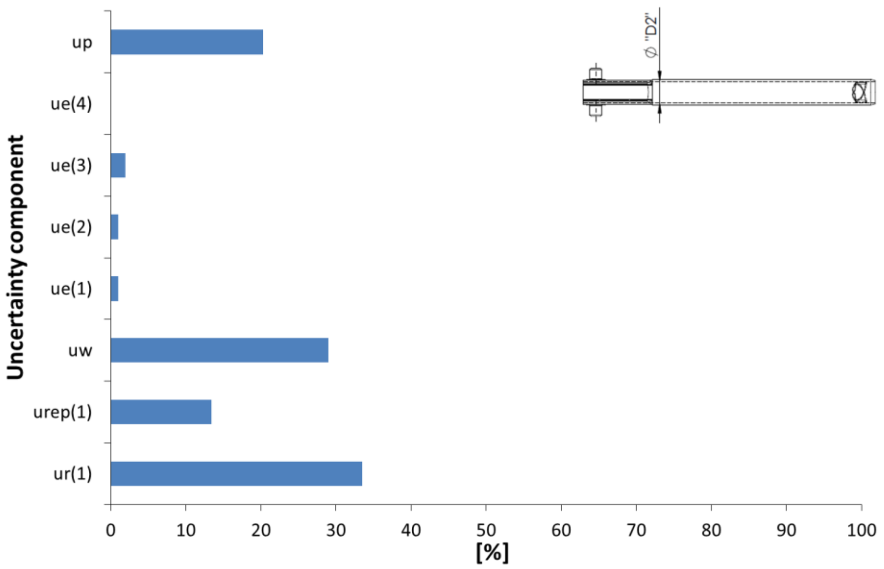


Figure 27: Item 2, ID no. 2, diameter D2, Distribution of uncertainty components.

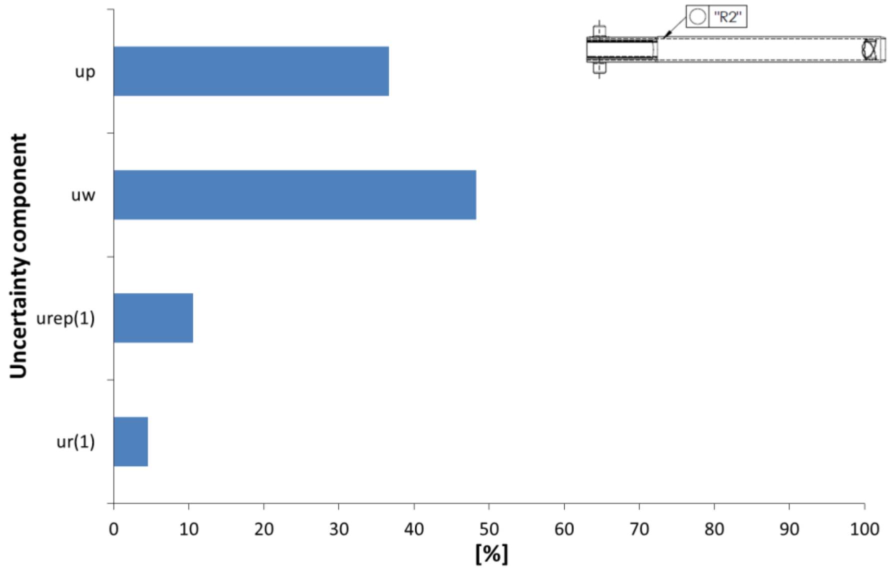


Figure 28: Item 2, ID no. 2, roundness R2, Distribution of uncertainty components.

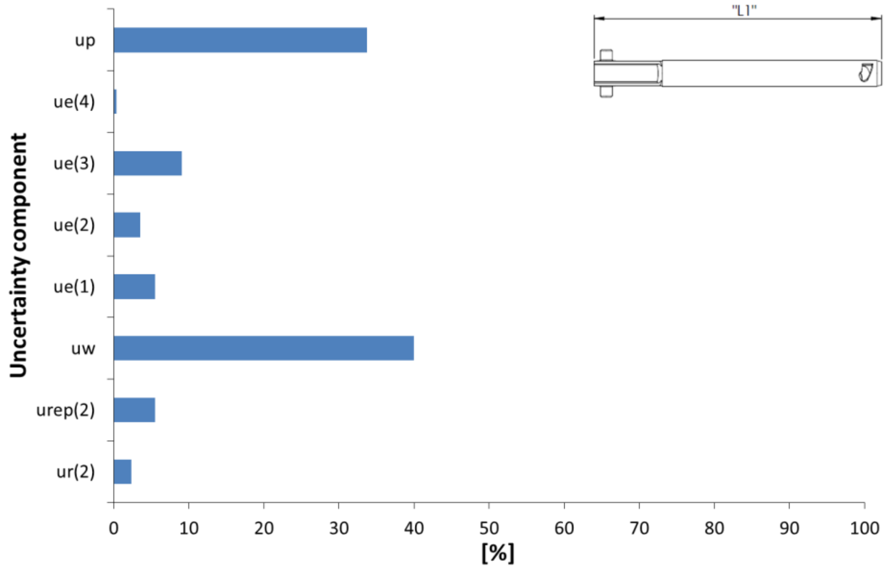


Figure 29: Item 2, ID no. 2, length L1, Distribution of uncertainty components.

3.2.4. Summarized bias and uncertainty budgets

3.2.4.1. Summarized bias and uncertainty budgets examples for Item 2 ID no. 2 before circulation

3.2.4.1.1. Item 2, ID no. 2, Length L1

A summarized overview example of a bias and uncertainty budget can be seen in Table 23 for Item 2 ID no. 2 for the case length *L1* before circulation.

Table 23: Item 2, ID no. 2, length L1, summarized overview of bias and uncertainty budgets.

Uncorrected measurement results				
Category	Measurand	Symbol	No. of measurements	Estimate [mm]
Average, from repeated measurements	*L1*	$\overline{Y}$	5	46.3650

Bias budget			
Category	Symbol	Systematic contributor	Estimate [µm]
Reference standard	$b_{r(2)}$	Compensation of systematic deviation due to reference artifact (gauge block, 50 mm)	0.40
Environment	$b_{e(2)}$	Compensation of systematic deviation due to temperature (gauge block, 50 mm)	-0.30
	$b_{e(3)}$	Compensation of systematic deviation due to temperature (work piece)	0.09
Total bias	b	Compensation of total systematic deviation due to all biases	0.19

Uncertainty budget			
Category	Symbol	Uncertainty contributor	Estimate [µm]
Reference standard	$u_{r(2)}$	Uncertainty component from gauge block, 50 mm	0.06
Measuring instrument	$u_{rep(2)}$	Uncertainty component from repeatability on gauge block, 50 mm	0.14
Workpiece	u_w	Uncertainty component from work piece	1.02
Environment	$u_{e(1)}$	Uncertainty component from temperature difference between workpiece and instrument	0.14
	$u_{e(2)}$	Uncertainty component from temperature deviation from standard reference temperature for instrument	0.09
	$u_{e(3)}$	Uncertainty component from temperature deviation from standard reference temperature for workpiece	0.23
	$u_{e(4)}$	Uncertainty component from workpiece expansion coefficient uncertainty	0.01
Procedure	u_p	Uncertainty component from measurement process	0.86
Combined standard uncertainty	u_c	Combined standard uncertainty	1.37
Expanded uncertainty (k=2)	U	Expanded uncertainty	2.74

3.3. Reference values

The reference values before the circulation for Item 2 and their corresponding uncertainties are shown in this section compared to the reference values after the circulation. A measuring uncertainty at 95% level (k=2) is used for all CGM values. Furthermore the E_n values are informed.

3.3.1. Diameter D1

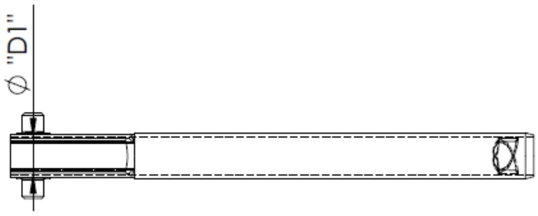


Table 24: Item 2 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 2, *D1*	Before circulation		After circulation		
ID no.	Y	U	Y	U	|En| [-]
1	3.4019	0.0008	3.4018	0.0014	0.0
2	3.4026	0.0010	3.4026	0.0010	0.0
3	3.4192	0.0020	3.4195	0.0009	0.1
4	3.4070	0.0019	3.4067	0.0009	0.1
5	3.4026	0.0015	3.4029	0.0009	0.2
6	3.4003	0.0011	3.4003	0.0008	0.0
7	3.4001	0.0019	3.4001	0.0008	0.0
8	3.4025	0.0013	3.4026	0.0009	0.1
9	3.4032	0.0021	3.4033	0.0009	0.0
10	3.4024	0.0021	3.4023	0.0008	0.1
11	3.4035	0.0026	3.4040	0.0009	0.2
12	3.4012	0.0010	3.4012	0.0008	0.0
13	3.4038	0.0018	3.4041	0.0009	0.1
14	3.4027	0.0018	3.4024	0.0009	0.2
15	3.4022	0.0008			
16	3.4086	0.0011	3.4087	0.0008	0.1
17	3.4026	0.0019	3.4027	0.0008	0.1
18	3.4055	0.0016	3.4056	0.0008	0.1
19	3.4071	0.0023	3.4073	0.0008	0.1
20	3.4076	0.0010	3.4075	0.0014	0.1
21	3.3999	0.0014	3.3999	0.0019	0.0
22	3.3964	0.0013	3.3966	0.0008	0.2
23	3.4097	0.0012	3.4098	0.0008	0.1
24	3.3977	0.0011	3.3976	0.0008	0.1
25	3.3992	0.0010	3.3994	0.0008	0.2
26	3.4041	0.0009	3.4040	0.0009	0.1
27	3.3999	0.0010	3.3998	0.0009	0.1
28	3.3913	0.0008	3.3915	0.0008	0.2
29	3.3957	0.0014	3.3957	0.0008	0.0
AVG		0.0014		0.0009	0.1
MAX		0.0026		0.0019	0.2
MIN		0.0008		0.0008	0.0

3.3.2. Roundness R1

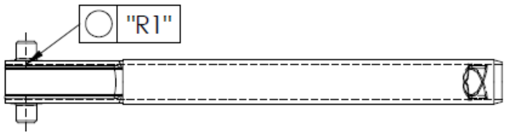


Table 25: Item 2 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 2. *R1*	Before circulation		After circulation		
ID no.	Y	U	Y	U	|En| [-]
1	0.0038	0.0007	0.0044	0.0008	0.6
2	0.0035	0.0008	0.0035	0.0028	0.0
3	0.0044	0.0024	0.0053	0.0064	0.1
4	0.0053	0.0008	0.0064	0.0007	1.0
5	0.0032	0.0009	0.0039	0.0007	0.6
6	0.0036	0.0015	0.0034	0.0009	0.1
7	0.0036	0.0036	0.0043	0.0013	0.2
8	0.0043	0.0019	0.0031	0.0005	0.6
9	0.0039	0.0044	0.0037	0.0006	0.1
10	0.0036	0.0030	0.0041	0.0008	0.2
11	0.0051	0.0019	0.0048	0.0010	0.1
12	0.0037	0.0011	0.0040	0.0009	0.2
13	0.0048	0.0009	0.0043	0.0011	0.3
14	0.0036	0.0010	0.0045	0.0034	0.2
15	0.0038	0.0013			
16	0.0064	0.0005	0.0072	0.0006	1.2
17	0.0048	0.0024	0.0050	0.0007	0.1
18	0.0045	0.0024	0.0047	0.0010	0.1
19	0.0045	0.0009	0.0047	0.0010	0.1
20	0.0039	0.0008	0.0047	0.0041	0.2
21	0.0040	0.0032	0.0031	0.0006	0.3
22	0.0043	0.0009	0.0044	0.0008	0.1
23	0.0051	0.0022	0.0046	0.0007	0.2
24	0.0055	0.0006	0.0054	0.0011	0.0
25	0.0042	0.0036	0.0035	0.0008	0.2
26	0.0035	0.0013	0.0033	0.0013	0.1
27	0.0062	0.0009	0.0064	0.0011	0.1
28	0.0045	0.0024	0.0037	0.0009	0.3
29	0.0053	0.0012	0.0052	0.0006	0.1

AVG		0.0017		0.0013	0.3
MAX		0.0064		0.0064	1.2
MIN		0.0032		0.0005	0.0

3.3.3. Diameter D2

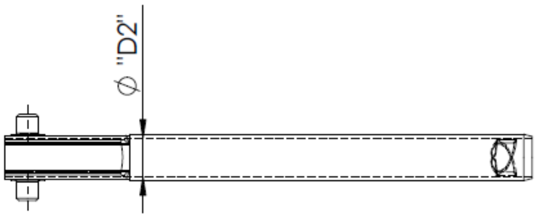


Table 26: Item 2 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 2. *D2*	Before circulation		After circulation		
ID no.	Y	U	Y	U	|En| [-]
1	3.4053	0.0009	3.4055	0.0008	0.2
2	3.3973	0.0011	3.3975	0.0008	0.2
3	3.4073	0.0020	3.4074	0.0008	0.0
4	3.4068	0.0011	3.4064	0.0009	0.3
5	3.4018	0.0010	3.4017	0.0009	0.0
6	3.4050	0.0013	3.4050	0.0008	0.0
7	3.4035	0.0029	3.4032	0.0010	0.1
8	3.4025	0.0017	3.4024	0.0009	0.1
9	3.4035	0.0034	3.4034	0.0009	0.0
10	3.4044	0.0024	3.4044	0.0009	0.0
11	3.4065	0.0017	3.4066	0.0008	0.1
12	3.4037	0.0013	3.4036	0.0009	0.0
13	3.4056	0.0019	3.4059	0.0008	0.1
14	3.4033	0.0011	3.4031	0.0008	0.1
15	3.4044	0.0014			
16	3.4065	0.0009	3.4066	0.0008	0.1
17	3.4082	0.0020	3.4081	0.0009	0.0
18	3.4064	0.0021	3.4063	0.0008	0.0
19	3.4075	0.0011	3.4072	0.0009	0.1
20	3.4096	0.0010	3.4094	0.0012	0.1
21	3.4091	0.0026	3.4094	0.0009	0.1
22	3.3982	0.0011	3.3983	0.0009	0.1
23	3.4091	0.0019	3.4092	0.0008	0.1
24	3.4028	0.0011	3.4028	0.0009	0.0
25	3.4043	0.0028	3.4039	0.0009	0.1
26	3.4095	0.0013	3.4097	0.0008	0.1
27	3.4031	0.0012	3.4028	0.0012	0.1
28	3.3978	0.0008	3.3979	0.0008	0.0
29	3.4059	0.0017	3.4061	0.0008	0.1
AVG		0.0016		0.0009	0.1
MAX		0.0034		0.0012	0.3
MIN		0.0008		0.0008	0.0

3.3.4. Roundness R2

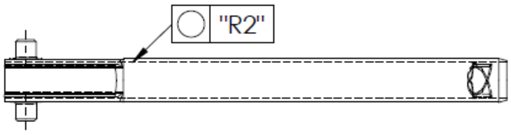


Table 27: Item 2 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 2, *R2*	Before circulation		After circulation		
ID no.	Y	U	Y	U	|En| [-]
1	0.0084	0.0005	0.0080	0.0010	0.3
2	0.0550	0.0016	0.0549	0.0010	0.1
3	0.0046	0.0015	0.0048	0.0006	0.1
4	0.0053	0.0006	0.0068	0.0013	1.0
5	0.0059	0.0011	0.0081	0.0011	1.4
6	0.0072	0.0011	0.0073	0.0021	0.1
7	0.0052	0.0010	0.0090	0.0010	2.8
8	0.0067	0.0005	0.0072	0.0010	0.5
9	0.0068	0.0007	0.0059	0.0012	0.6
10	0.0071	0.0011	0.0090	0.0015	1.0
11	0.0089	0.0011	0.0074	0.0010	1.0
12	0.0062	0.0020	0.0061	0.0008	0.0
13	0.0087	0.0034	0.0089	0.0018	0.0
14	0.0079	0.0008	0.0086	0.0009	0.6
15	0.0070	0.0011			
16	0.0070	0.0011	0.0082	0.0032	0.3
17	0.0055	0.0011	0.0071	0.0012	1.0
18	0.0064	0.0009	0.0084	0.0020	0.9
19	0.0075	0.0011	0.0102	0.0010	1.8
20	0.0067	0.0012	0.0094	0.0016	1.4
21	0.0119	0.0021	0.0139	0.0023	0.6
22	0.0108	0.0009	0.0132	0.0022	1.0
23	0.0129	0.0023	0.0114	0.0016	0.5
24	0.0122	0.0012	0.0132	0.0009	0.7
25	0.0106	0.0013	0.0130	0.0010	1.5
26	0.0120	0.0006	0.0121	0.0008	0.2
27	0.0120	0.0008	0.0112	0.0007	0.7
28	0.0116	0.0014	0.0132	0.0009	1.0
29	0.0092	0.0020	0.0118	0.0019	0.9
AVG		0.0012		0.0013	0.8
MAX		0.0034		0.0032	2.8
MIN		0.0005		0.0006	0.0

3.3.5. Length L1

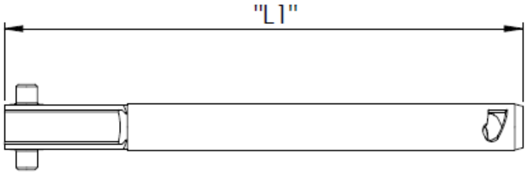


Table 28: Item 2 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

Item 2, *L1*	Before circulation		After circulation		
ID no.	Y	U	Y	U	|En| [-]
1	46.3550	0.0016	46.3559	0.0021	0.3
2	46.3648	0.0027	46.3651	0.0017	0.1
3	46.3477	0.0030	46.3483	0.0018	0.2
4	46.3553	0.0012	46.3555	0.0015	0.1
5	46.3981	0.0037	46.3975	0.0018	0.2
6	46.3392	0.0021	46.3392	0.0022	0.0
7	46.3572	0.0010	46.3562	0.0008	0.8
8	46.3551	0.0039	46.3552	0.0028	0.0
9	46.3714	0.0013	46.3709	0.0015	0.2
10	46.3478	0.0033	46.3491	0.0009	0.4
11	46.3628	0.0026	46.3628	0.0011	0.0
12	46.3620	0.0035	46.3630	0.0013	0.3
13	46.3629	0.0052	46.3610	0.0014	0.3
14	46.3638	0.0017	46.3633	0.0022	0.2
15	46.3551	0.0025			
16	46.3493	0.0011	46.3493	0.0012	0.0
17	46.3594	0.0023	46.3606	0.0011	0.5
18	46.3422	0.0020	46.3432	0.0017	0.4
19	46.3372	0.0030	46.3369	0.0025	0.1
20	46.3511	0.0032	46.3509	0.0010	0.1
21	46.3830	0.0039	46.3823	0.0007	0.2
22	46.3686	0.0017	46.3676	0.0014	0.4
23	46.3816	0.0018	46.3814	0.0007	0.1
24	46.3783	0.0012	46.3777	0.0017	0.3
25	46.3793	0.0016	46.3795	0.0010	0.1
26	46.3851	0.0017	46.3845	0.0012	0.3
27	46.3769	0.0027	46.3763	0.0016	0.2
28	46.3711	0.0026	46.3708	0.0013	0.1
29	46.3789	0.0027	46.3789	0.0009	0.0

AVG		0.0025		0.0015	0.2
MAX		0.0052		0.0028	0.8
MIN		0.0010		0.0007	0.0

3.4. Analysis of reference measurement data

The variation of the reference measurements, can be used to evaluate repeatability and consistency of measurements [Hansen et al., 1996] [De Chiffre et al., 2004]. In this section examples are shown for Item 2 with the ID no. 2.

The measurements for the reference values before the circulation are given in Figure 31 to the left for all the measurands. Furthermore the measurements for the reference values after the circulation are given in Figure 31 to the right. Notice that the deviation of each measurement is based on the deviation between the measured value and the average value of the measurements. The variations do not exceed 2 µm in both cases for all the measurands.

It is clear that the roundness of the measurand *R2* is bad compared to *R1*, see Figure 32 and Figure 33. It is clear that the metal tube has been deformed in the case of *R2*, when ID 2 is compared to the other IDs, since the form of the roundness should be similar to *R1*. The deformation could be due to the tightening during the fixture process for the reference measurements or a faulty manufacture during the process of production. Furthermore *R2* is more exposed to deformations compared to *R1*, because *R2* has a lower wall thickness compared to *R1*.

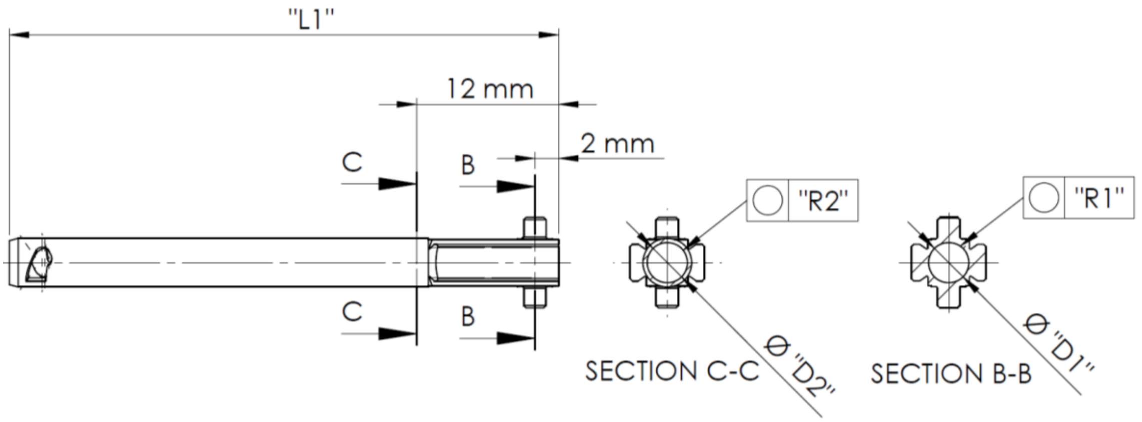


Figure 30: Item 2 – Overview of all the measurands; L1, D1, R1, D2 and R2.

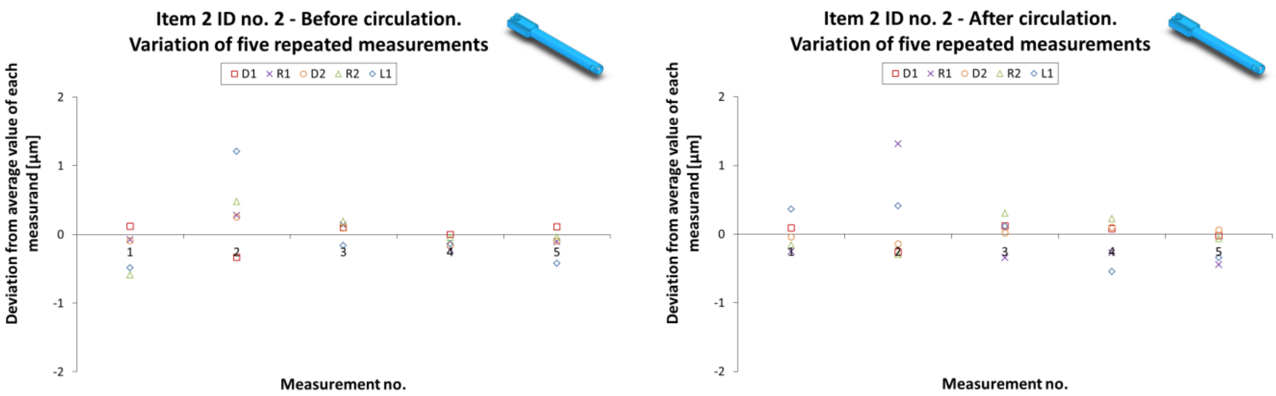


Figure 31: Item 2 ID no. 2 - Variation of five repeated measurements, before circulation (left) and after circulation (right).

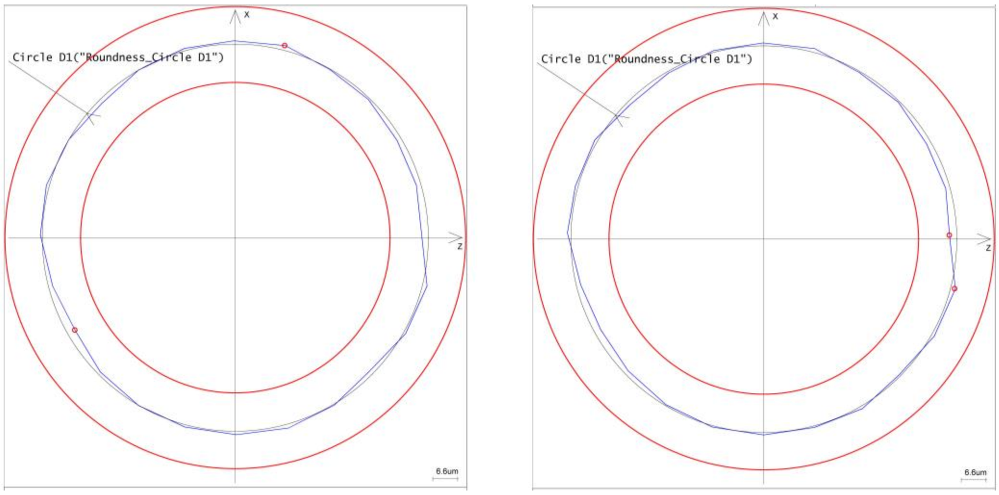


Figure 32: Item 2 ID no. 2 – Form of the roundness R1, before circulation (left) and after circulation (right).

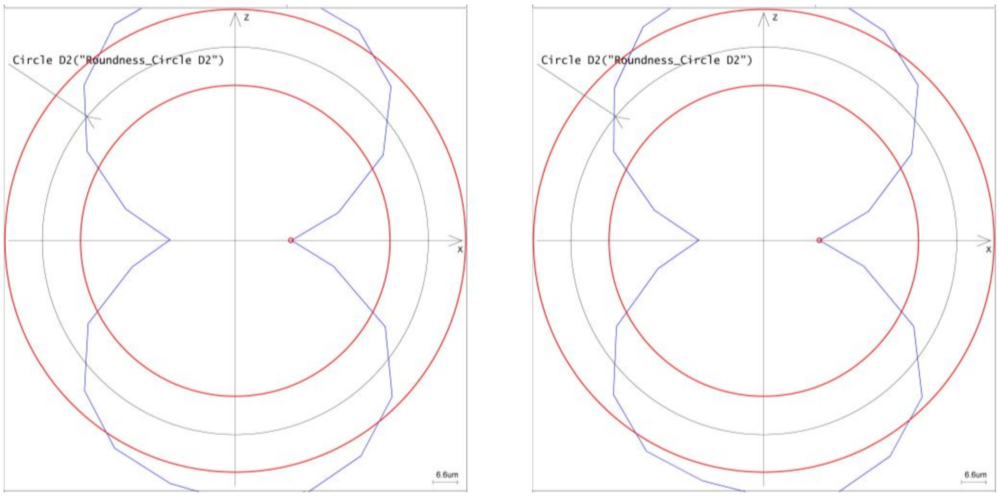


Figure 33: Item 2 ID no. 2 – Form of the roundness R2, before circulation (left) and after circulation (right).

3.5. Comparison of values after circulation with reference values before circulation

For Item 2 most E_n values are acceptable, except for *R2*, see Figure 34, probably due to the lower wall thickness compared to *R1*, which makes it more sensitive to deformation. An example of a deformed tube for *R2* is given in Figure 35 for Item 2 ID 19.

For Item 2, reference values are estimated based on the average values of the two measurement rounds, when all dataset are available. For Item 2, the uncertainty for each ID is assumed to be the maximum uncertainty through the two measurement rounds.

The calculated reference values and their corresponding uncertainties are shown in Table 29.

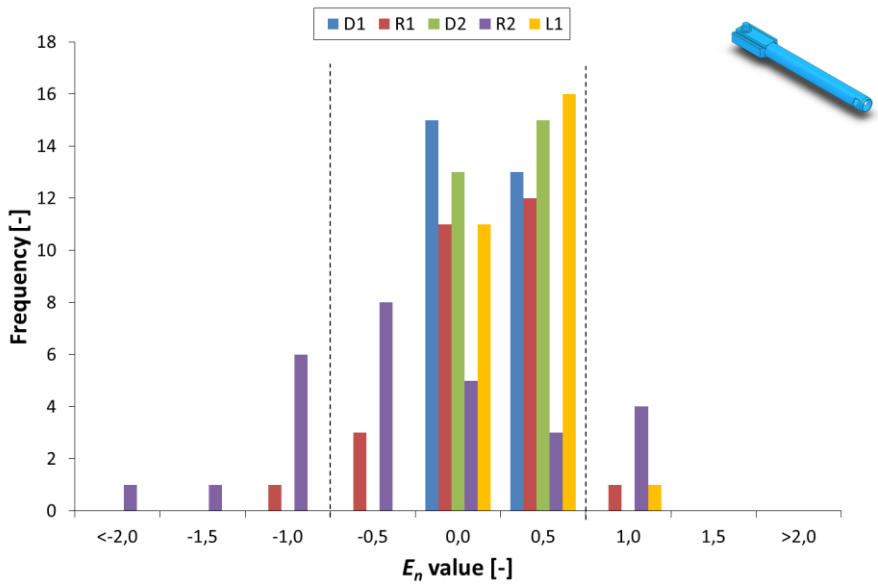
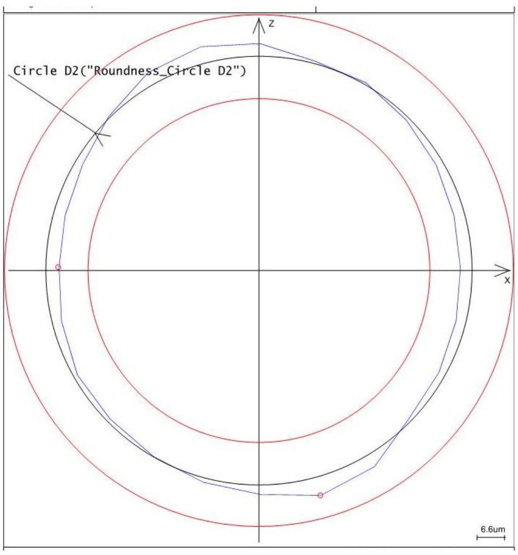


Figure 34: Item 2 – Histogram of E_n values for all measurands. Before vs. after circulation.



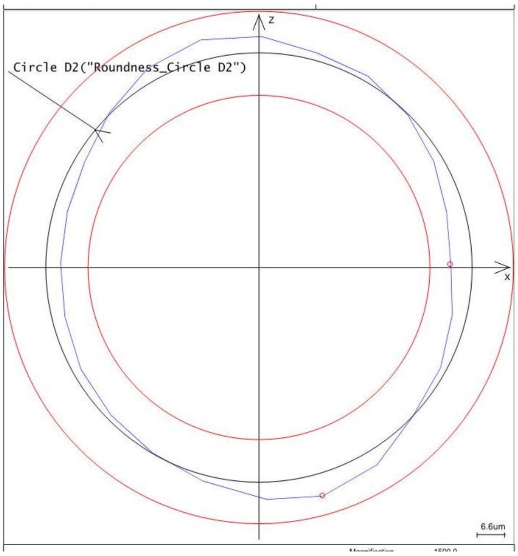


Figure 35: Item 2 ID no. 19 – Form of the roundness R2, before circulation (left) and after circulation (right).

Table 29: Item 2 – Reference values and their corresponding expanded uncertainties (k=2). Values are in mm.

	Diameter *D1*		Roundness *R1*		Diameter *D2*		Roundness *R2*		Length *L1*	
ID no.	Y	U	Y	U	Y	U	Y	U	Y	U
1	3.4018	0.0014	0.0041	0.0008	3.4054	0.0009	0.0082	0.0010	46.3555	0.0021
2	3.4026	0.0010	0.0035	0.0028	3.3974	0.0011	0.0550	0.0016	46.3650	0.0027
3	3.4193	0.0020	0.0049	0.0064	3.4073	0.0020	0.0047	0.0015	46.3480	0.0030
4	3.4068	0.0019	0.0059	0.0008	3.4066	0.0011	0.0061	0.0013	46.3554	0.0015
5	3.4027	0.0015	0.0035	0.0009	3.4018	0.0010	0.0070	0.0011	46.3978	0.0037
6	3.4003	0.0011	0.0035	0.0015	3.4050	0.0013	0.0072	0.0021	46.3392	0.0022
7	3.4001	0.0019	0.0039	0.0036	3.4034	0.0029	0.0071	0.0010	46.3567	0.0010
8	3.4025	0.0013	0.0037	0.0019	3.4025	0.0017	0.0069	0.0010	46.3551	0.0039
9	3.4032	0.0021	0.0038	0.0044	3.4035	0.0034	0.0064	0.0012	46.3711	0.0015
10	3.4024	0.0021	0.0039	0.0030	3.4044	0.0024	0.0080	0.0015	46.3484	0.0033
11	3.4037	0.0026	0.0049	0.0019	3.4065	0.0017	0.0081	0.0011	46.3628	0.0026
12	3.4012	0.0010	0.0039	0.0011	3.4036	0.0013	0.0061	0.0020	46.3625	0.0035
13	3.4039	0.0018	0.0045	0.0011	3.4057	0.0019	0.0088	0.0034	46.3619	0.0052
14	3.4025	0.0018	0.0040	0.0034	3.4032	0.0011	0.0083	0.0009	46.3636	0.0022
15	3.4022	0.0008	0.0038	0.0013	3.4044	0.0014	0.0070	0.0011	46.3551	0.0025
16	3.4087	0.0011	0.0068	0.0006	3.4066	0.0009	0.0076	0.0032	46.3493	0.0012
17	3.4027	0.0019	0.0049	0.0024	3.4081	0.0020	0.0063	0.0012	46.3600	0.0023
18	3.4055	0.0016	0.0046	0.0024	3.4063	0.0021	0.0074	0.0020	46.3427	0.0020
19	3.4072	0.0023	0.0046	0.0010	3.4073	0.0011	0.0088	0.0011	46.3371	0.0030
20	3.4075	0.0014	0.0043	0.0041	3.4095	0.0012	0.0080	0.0016	46.3510	0.0032
21	3.3999	0.0019	0.0036	0.0032	3.4093	0.0026	0.0129	0.0023	46.3826	0.0039
22	3.3965	0.0013	0.0043	0.0009	3.3983	0.0011	0.0120	0.0022	46.3681	0.0017
23	3.4098	0.0012	0.0048	0.0022	3.4091	0.0019	0.0121	0.0023	46.3815	0.0018
24	3.3977	0.0011	0.0055	0.0011	3.4028	0.0011	0.0127	0.0012	46.3780	0.0017
25	3.3993	0.0010	0.0038	0.0036	3.4041	0.0028	0.0118	0.0013	46.3794	0.0016
26	3.4041	0.0009	0.0034	0.0013	3.4096	0.0013	0.0121	0.0008	46.3848	0.0017
27	3.3999	0.0010	0.0063	0.0011	3.4029	0.0012	0.0116	0.0008	46.3766	0.0027
28	3.3914	0.0008	0.0041	0.0024	3.3979	0.0008	0.0124	0.0014	46.3709	0.0026
29	3.3957	0.0014	0.0052	0.0012	3.4060	0.0017	0.0105	0.0020	46.3789	0.0027

AVG		0.0015		0.0021		0.0016		0.0016		0.0025
MAX		0.0026		0.0064		0.0034		0.0034		0.0052
MIN		0.0008		0.0006		0.0008		0.0008		0.0010

3.6. Conclusion

The coordinate measuring machine used at CGM to measure Item 2 is a mechanical CMM equipped with a dynamic probe. The CMM is of the type Zeiss OMC 850. The CMM is placed in a temperature controlled room (T = 20 °C ± 1.0 °C and a maximum of 60 % RH).

The PUMA approach [ISO 14253-2, 2011] is used for uncertainty estimation, which is a simplification of GUM approach [ISO/IEC Guide 98-3, 2008].

The variations do not exceed 2 µm for the repeated measurements.

In order to judge the agreement between measurements through time, the E_n value normalised with respect to the stated uncertainty was computed according to ISO 17043 guidelines [ISO/IEC 17043, 2010]. If $|E_n| < 1$ the quality of the measurement result is acceptable, while it is not acceptable if $|E_n| \geq 1$.

Reference measurements were carried out by CGM, before circulation, in December 2012 – March 2013. These values were verified by new measurements after circulation, in the period February – August 2013. For Item 2 most E_n values are acceptable, except for *R2*, probably due to the lower wall thickness compared to *R1*, which makes it more sensitive to deformation.

For Item 2, reference values are estimated based on the average values of the two measurement rounds, when all dataset are available. For Item 2, the uncertainty for each ID is assumed to be the maximum uncertainty through the two measurement rounds.

Expanded measurement uncertainties obtained by CGM were in the range of 1.5-2.5 µm for the metal part.

4. References

[De Chiffre et al., 2004] L. De Chiffre, H. N. Hansen, R. E. Morace, CIRP Interlaboratory Comparison of Coordinate Measuring Machines using an Optomechanical Hole Plate, Publication no. IPL.141.04 (MM04.40), DTU, Technical University of Denmark, November 2004.

[Hansen et al., 1996] H. N. Hansen, L. De Chiffre, Nordic Audit of Coordinate Measuring Machines, EUROMET Project No 330, Nordic Industrial Fund Project No P93046, Technical University of Denmark, May 1996.

[ISO 14253-2, 2011] ISO 14253-2:2011, Geometrical product specifications (GPS) -- Inspection by measurement of workpieces and measuring equipment -- Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification.

[ISO/IEC 17043, 2010] ISO/IEC 17043:2010, Conformity assessment, General requirements for proficiency testing.

[ISO/IEC Guide 98-3, 2008] ISO/IEC Guide 98-3, 2008, Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995).

[Kalpakjian, 2008] Manufacturing Processes for Engineering Materials, 5th ed. Kalpakjian, Schmid © 2008, Pearson Education ISBN No. 0-13-227271-7.

[Popov, 2010] V.L. Popov, Contact Mechanics and Friction, DOI 10.1007/978-3-642-10803-7_5, © Springer-Verlag Berlin Heidelberg 2010

[Technical Protocol] J. Angel, L. De Chiffre, E. Larsen, J. Rasmussen, CIA-CT comparison, Inter laboratory comparison on Industrial Computed Tomography, Technical Protocol, Department of Mechanical Engineering, Technical University of Denmark, 2012.

5. Appendix

Uncorrected measurement example for Item 1 ID no. 2 before circulation
Bias budget example for Item 1 ID no. 2 before circulation
- Item 1, ID no. 2, Diameter D1
- Item 1, ID no. 2, Roundness R1
- Item 1, ID no. 2, Length L1

Uncertainty budget example for Item 1 ID no. 2 before circulation
- Item 1, ID no. 2, Diameter D1
- Item 1, ID no. 2, Roundness R1
- Item 1, ID no. 2, Length L1

Uncorrected measurement example for Item 2 ID no. 2 before circulation
Bias budget example for Item 2 ID no. 2 before circulation
- Item 2, ID no. 2, Diameter D1
- Item 2, ID no. 2, Roundness R1
- Item 2, ID no. 2, Diameter D2
- Item 2, ID no. 2, Roundness R2
- Item 2, ID no. 2, Length L1

Uncertainty budget example for Item 2 ID no. 2 before circulation
- Item 2, ID no. 2, Diameter D1
- Item 2, ID no. 2, Roundness R1
- Item 2, ID no. 2, Diameter D2
- Item 2, ID no. 2, Roundness R2
- Item 2, ID no. 2, Length L1

Example on the measurement protocol for Item 1
Example on the measurement protocol for Item 2

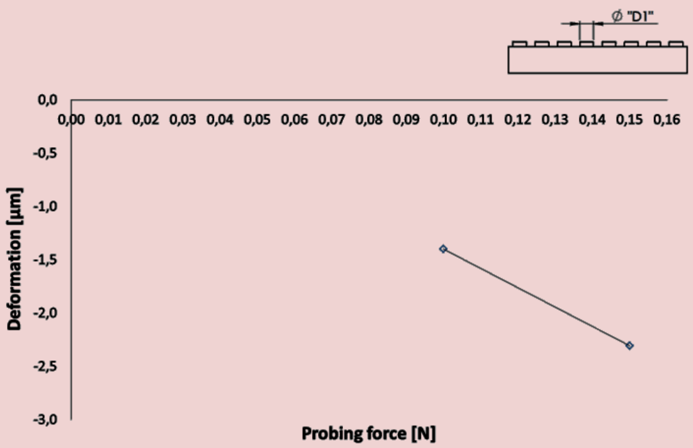
5.1.1.1. Uncorrected measurement example for Item 1 ID no. 2 before circulation

List of the uncorrected measurement results at CGM					
Category	Measurand	Symbol	No. of measurements	Measured size [mm]	Estimate [mm]
Average, from repeated measurements	*D1*, un-filtered	$\overline{Y}$	1	4.90281	4.90281
Average, from repeated measurements	*D1*, filter Gauss 150	$\overline{Y}$	1	4.90281	4.90281
Average, from repeated measurements	*R1*, un-filtered	$\overline{Y}$	1	0.00373	0.00373
Average, from repeated measurements	*R1*, filter Gauss 150	$\overline{Y}$	1	0.00304	0.00304
Average, from repeated measurements	*L1*	$\overline{Y}$	1	55.95816	55.95816
Average, from repeated measurements	Ø 8 mm calibration sphere. diameter	$\overline{Y}$	10	7.99990 8.00000 8.00000 7.99990 7.99990 7.99990 7.99990 7.99990 7.99990 8.00000	7.99993
Average, from repeated measurements	Ø 8 mm calibration sphere. roundness	$\overline{Y}$	10	0.00140 0.00360 0.00330 0.00100 0.00110 0.00130 0.00130 0.00110 0.00130 0.00110	0.00165
Average, from repeated measurements	Zerodur plate, 100 mm between hole no. 5 and 7	$\overline{Y}$	10	100.00880 100.00882 100.00882 100.00880 100.00880 100.00884 100.00889 100.00888 100.00891 100.00890	100.00885

5.1.1.2. Bias budget example for Item 1 ID no. 2 before circulation

The bias budget example for Item 1 ID no. 2 before circulation is divided in three sub-budgets; the diameter *D1*, the roundness *R1* and the length *L1*.

5.1.1.2.1. Item 1, ID no. 2, Diameter D1

Item 1, ID no. 2, Diameter D1, Detailed description of the compensation of systematic deviations			
Category	Symbol	Comments and procedure	Estimate [µm]
Environment	$b_{e(1)}$	Compensation of systematic deviation due to measuring force (work piece) The average value has been compensated for the systematic error due to the force from the probe. For this the deflection from a contribution of the deviation between 0.15 N and 0.10 N, since these have been compensated for a force of 0.05 N for creating a zero point. The deviated deflection can be read off to be -0.91 µm.  It means that the measuring result with compensation can be written as the summation of the original average value and 2×the compensated force, since the probe acts on both sides, when measuring, so ($b_{e(1)}$): $b_{e(1)} = -2 \times 0.91 \mu m = -1.82 \mu m$	-1.82
Total bias	b	Compensation of total systematic deviation due to all biases The total systematic error can be written as the summation of all the systematic errors $b = b_{e(1)} = -1.82 \mu m$	-1.82

5.1.1.2.2. Item 1, ID no. 2, Roundness R1

Item 1, ID no. 2, Roundness R1, Detailed description of the compensation of systematic deviations			
Category	Symbol	Comments and procedure	Estimate [µm]
Total bias	b	Compensation of total systematic deviation due to all biases The total systematic error can be written as the summation of all the systematic errors $b = 0.00 \mu m$	0.00

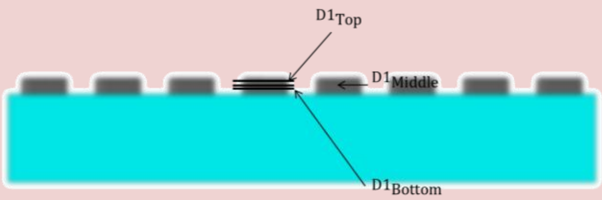
5.1.1.2.3. Item 1, ID no. 2, Length L1

Item 1, ID no. 2, Length L1, Detailed description of the compensation of systematic deviations			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$b_{r(2)}$	Compensation of systematic deviation due to reference artifact (zerodur plate) The compensation is based on 10 repeated measurements on a zerodur plate with a nominal length between holes of 100 mm (between hole no. 5 and 7) with the reference value $x = 100.0067mm$, where the measurements result in an average value of $\overline{Y} = 100.0089mm$. $b_{r(2)} = \overline{Y} - x = 100.0089mm - 100.0067mm = 2.20\mu m$	2.20
Total bias	b	Compensation of total systematic deviation due to all biases The total systematic error can be written as the summation of all the systematic errors $b = b_{r(2)} = 2.20\mu m$	2.20

5.1.1.3. *Uncertainty budget example for Item 1 ID no. 2 before circulation*

The uncertainty budget example for Item 1 ID no. 2 before circulation is divided in three sub-budgets; the diameter *D1*, the roundness *R1* and the length *L1*.

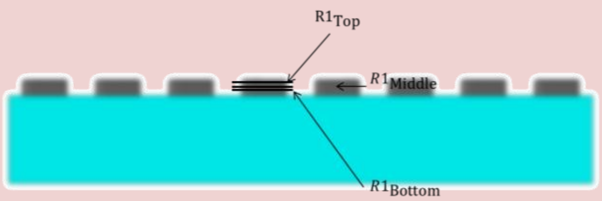
5.1.1.3.1. *Item 1, ID no. 2, Diameter D1*

Item 1, ID no. 2, Diameter D1, Detailed description of the procedure for each of the uncertainty contributions			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$u_{r(1)}$	<u>Uncertainty component from calibration sphere, Ø8 mm</u> A calibration sphere with a nominal diameter of Ø8 mm is used as reference. The central diameter coincides within ± 0.20 µm. The uncertainty from the certificate of the calibration sphere is given with a coverage factor k =2 (95% confidence level). The standard uncertainty can be written as: $u_r = \frac{0.20\,\mu m}{2} = 0.10\,\mu m$	0.10
Measuring instrument	$u_{rep(1)}$	<u>Uncertainty component from repeatability on calibration sphere, Ø8 mm</u> This component is a type A evaluation and is estimated to follow a Gaussian distribution. The repeatability was evaluated based on a Ø8 mm calibration sphere with 10 un-filtered replicates (n = 10) in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and $\alpha = 0.05$. Since s = 0.00005 mm, $t_{0.025} = 2.262$ with 9 degrees of freedom. It is assumed that $u_{rep(1)}$ can be written as: $u_{rep(1)} = s \cdot \frac{t}{\sqrt{n}} = 0.05\,\mu m \cdot \frac{2.262}{\sqrt{10}} = 0.04\,\mu m$	0.04
Workpiece	u_w	<u>Uncertainty component from work piece</u> Generally two cases contribute to the form error; (1) the alignment of datum A and (2) the roundness of the knob (R1). Instead it is assumed that the form can be estimated based on the deviation between the un-filtered maximum and minimum diameters for **<u>each sample</u>** in three levels of D1 (top 1.05 mm from datum A, middle 1.00 mm from datum A and bottom 0.95 mm from datum A), which cover the two contributes ((1) and (2)) to the form, so $form = \Delta D1 = MAX(D1_{Top}, D1_{Middle}, D1_{Bottom})$.  This component is a type B evaluation and the form is estimated to follow a rectangular distribution (b = 0.6), so it gives $u_w = form \cdot b = 0.00117mm \times 0.6 = 0.70\,\mu m$	0.70

Environment	$u_{e(1)}$	Uncertainty component from temperature difference between workpiece and instrument It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.5 °C. The nominal diameter $D = 4.9\,\text{mm}$ is used. $u_{e(1)} = \Delta T \cdot (\alpha_{workpiece} - \alpha_{instrument}) \cdot D \cdot b = 0.5°C \times (95 \times 10^{-6}\ \text{K}^{-1} - 0.0 \times 10^{-6}\ \text{K}^{-1})$ $\times 4.9\,\text{mm} \times 0.7 = 0.16\,\mu m$ A U- distribution is assumed (b = 0.7).	0.16
	$u_{e(2)}$	Uncertainty component from temperature deviation from standard reference temperature for instrument The temperature deviation is assumed to the same value as the temperature variation, 0.28 °C. The nominal diameter $D = 3.4\,\text{mm}$ is used. $u_{e(2)} = \Delta T \cdot (\alpha_{instrument}) \cdot D \cdot b = 0.28°C \times (0.0 \times 10^{-6}\ \text{K}^{-1}) \times 4.9\,\text{mm} \times 0.7$ $= 0.00\,\mu m$ A U- distribution is assumed (b = 0.7).	0.00
	$u_{e(3)}$	Uncertainty component from temperature deviation from standard reference temperature for workpiece It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.5 °C. The nominal diameter $D = 4.9\,\text{mm}$ is used. $u_{e(2)} = \Delta T \cdot (\alpha_{workpiece}) \cdot D \cdot b = 0.5°C \times (95 \times 10^{-6}\ \text{K}^{-1}) \times 4.9\,\text{mm} \times 0.7$ $= 0.16\,\mu m$ A U- distribution is assumed (b = 0.7).	0.16
	$u_{e(4)}$	Uncertainty component from workpiece expansion coefficient uncertainty The estimated range of the thermal expansion coefficient is ± 15 · 10^{-6} K^{-1}. The nominal diameter $D = 4.9\,\text{mm}$ is used. The maximum temperature difference from the standard reference temperature from the 30 samples is used to get an uncertainty component, which cover the data for all the samples. $\Delta T_{\max} = 20.63°C - 20.00°C = 0.63°C$. A U- distribution is assumed (*b = 0.7*), so the limit value is $u_{e(4)} = \Delta T_{\max} \cdot \Delta\alpha \cdot D \cdot b = 0.63°C \times 15 \times 10^{-6}\ \text{K}^{-1} \times 4.9\,\text{mm} \times 0.7 = 0.03\,\mu m$	0.03
	$u_{e(5)}$	Uncertainty component from measuring force If we assume that we have a contact between a rigid sphere and an elastic plane surface with a force F, a deformation occurs only on the elastic plane surface. The deformation can be written as [Popov, 2010] $y_t = \left(\frac{3}{4} F R^2 \left(\frac{1-v^2}{E}\right)\right)^{\frac{2}{3}} = \left(\frac{3}{4} 0.002N \cdot (0.0005m)^2 \left(\frac{1-0.35^2}{7.5 \cdot 10^9\ Pa}\right)\right)^{\frac{2}{3}} = 0.04\,\mu m$ Hence v is Poisson's ratio and E is the elasticity modulus. Radius of the probe, R = 0.5 mm = 0.0005 m. Resolution force of the used CMM, F = ± 1 mN = 2 mN = 0.002 N. Properties for Item 1 (ABS) are acquired from [Kalpakjian, 2008] with v = 0.35 and E = 7.5 GPa = 7.5 · 10^9 Pa. The deformation should be multiplied with 2, since the force acts on both sides on the rod. This component is a type B evaluation and is estimated to follow a rectangular distribution (b = 0.6), so it gives $u_{e(5)} = 2 \cdot y_t \cdot b = 2 \cdot 0.04\,\mu m \cdot 0.6 = 0.05\,\mu m$	0.05

Procedure	u_p	Uncertainty component from measurement process This component is a type A evaluation and is estimated to follow a Gaussian distribution. No replicates are performed for the 30 samples. Instead the repeatability was evaluated based on one single sample with 5 un-filtered replicates in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and $\alpha = 0.05$. Since s = 0,0001 mm, $t_{0.025} = 2.776$ with 4 degrees of freedom. It is assumed that u_p can be written as: $u_p = s \cdot \frac{t}{\sqrt{n}} = 0.1\,\mu m \cdot \frac{2.776}{\sqrt{5}} = 0.12\mu m$	0.12
Combined standard uncertainty	u_c	Combined standard uncertainty The combined standard uncertainty can be written as: $u_c = \sqrt{u_{r(1)}^2 + u_{rep(1)}^2 + u_w^2 + u_{e(1)}^2 + u_{e(2)}^2 + u_{e(3)}^2 + u_{e(4)}^2 + u_{e(5)}^2 + u_p^2}$ $= \sqrt{(0.10\mu m)^2 + (0.04\mu m)^2 + (0.70\mu m)^2 + (0.16\mu m)^2 + (0.00\mu m)^2 + (0.16\mu m)^2 + (0.03\mu m)^2 + (0.05\mu m)^2 + (0.12\mu m)^2}$ $= 0.76\mu m$	0.76
Expanded uncertainty (k=2)	U	Expanded uncertainty The expanded uncertainty can be written as: $U = k \cdot u_c = 2 \cdot 0.76\mu m = 1.51\mu m$	1.51

5.1.1.3.2. Item 1, ID no. 2, Roundness R1

Item 1, ID no. 2, Roundness R1, Detailed description of the procedure for each of the uncertainty contributions			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$u_{r(1)}$	Uncertainty component from calibration sphere, Ø8 mm A calibration sphere with a nominal diameter of Ø8 mm is used as reference. The central roundness coincides within ± 0.10 µm. The uncertainty from the certificate of the calibration sphere is given with a coverage factor k =2 (95% confidence level). The standard uncertainty can be written as: $u_{r(1)} = \frac{0.10\,\mu m}{2} = 0.05\,\mu m$	0.05
Measuring instrument	$u_{rep(1)}$	Uncertainty component from repeatability on calibration sphere, Ø8 mm This component is a type A evaluation and is estimated to follow a Gaussian distribution. The repeatability was evaluated based on a Ø8 mm calibration sphere with 10 un-filtered replicates (n = 10) in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0.00096 mm, $t_{0.025}$ = 2.262 with 9 degrees of freedom. It is assumed that $u_{rep(1)}$ can be written as: $u_{rep(1)} = s \cdot \frac{t}{\sqrt{n}} = 1.0\,\mu m \cdot \frac{2.262}{\sqrt{10}} = 0.88\,\mu m$	0.88
Workpiece	u_w	Uncertainty component from work piece Generally two cases contribute to the form error; (1) the alignment of datum A and (2) the roundness of the knob (R1). Instead it is assumed that the form error can be estimated based on the deviation between the un-filtered maximum and minimum roundness for **each sample** in three levels of R1 (top 1.05 mm from datum A, middle 1.00 mm from datum A and bottom 0.95 mm from datum A), which cover the two contributes ((1) and (2)) to the form error, so $form\,error = \Delta R1 = MAX(R1_{Top}, R1_{Middle}, R1_{Bottom})$.  This component is a type B evaluation and the form is estimated to follow a rectangular distribution (b = 0.6), so it gives $u_w = form \cdot b = 0.00107mm \times 0.6 = 0.64\,\mu m$	0.64
Procedure	u_p	Uncertainty component from measurement process This component is a type A evaluation and is estimated to follow a Gaussian distribution. No replicates are performed for the 30 samples. Instead the repeatability was evaluated based on one single sample with 5 un-filtered replicates in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0,0001 mm, $t_{0.025}$ = 2.776 with 4 degrees of freedom. It is assumed that u_p can be written as: $u_p = s \cdot \frac{t}{\sqrt{n}} = 0.1\,\mu m \cdot \frac{2.776}{\sqrt{5}} = 0.12\,\mu m$	0.12

Combined standard uncertainty	u_c	Combined standard uncertainty The combined standard uncertainty can be written as: $u_c = \sqrt{u_{r(1)}^2 + u_{rep(1)}^2 + u_w^2 + u_p^2} = \sqrt{(0.05\mu m)^2 + (0.88\mu m)^2 + (0.64\mu m)^2 + (0.12\mu m)^2}$ $= 1.10\mu m$	1.10
Expanded uncertainty (k=2)	U	Expanded uncertainty The expanded uncertainty can be written as: $U = k \cdot u_c = 2 \cdot 1.10\mu m = 2.20\mu m$	2.20

5.1.1.3.3. Item 1, ID no. 2, Length L1

Item 1, ID no. 2, Length L1, Detailed description of the procedure for each of the uncertainty contributions			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$u_{r(2)}$	<u>Uncertainty component from zerodur plate, 100 mm</u> A zerodur plate with a nominal length between holes of 100 mm is used as reference. The central length coincides within ± 0.40 µm. The uncertainty from the certificate of the zerodur plate is given with a coverage factor k =2 (95% confidence level). The standard uncertainty can be written as: $u_{r(2)} = \frac{0.40\,\mu m}{2} = 0.20\,\mu m$	0.20
Measuring instrument	$u_{rep(2)}$	<u>Uncertainty component from repeatability on zerodur plate, 100 mm</u> This component is a type A evaluation and is estimated to follow a Gaussian distribution. The repeatability was evaluated based on a zerodur plate with 100 mm between two holes with 10 replicates (n = 10) in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0.00004 mm, $t_{0.025}$ = 2.262 with 9 degrees of freedom. It is assumed that $u_{rep(2)}$ can be written as: $u_{rep(2)} = s \cdot \frac{t}{\sqrt{n}} = 0.04\,\mu m \cdot \frac{2.262}{\sqrt{10}} = 0.03\mu m$	0.03
Workpiece	u_w	<u>Uncertainty component from work piece</u> Generally two cases contribute to the form of the work piece; (1) the parallelism of the two knobs (datum B and datum C) and (2) the roundness of the two knobs (datum B and datum C), which influences on the center position. Instead it is assumed that the form can be estimated based on the maximum deviation between the maximum and minimum lengths for **<u>each sample</u>** in three levels of L1 (top 1.05 mm from datum A, middle 1.00 mm from datum A and bottom 0.95 mm from datum A), which cover the two contributes ((1) and (2)) to the form, so $form = \Delta L1 = MAX(L1_{Top}, L1_{Middle}, L1_{Bottom})$  This component is a type B evaluation and the form is estimated to follow a rectangular distribution (b = 0.6), so it gives $u_w = form \cdot b = 0.00039 mm \times 0.6 = 0.23\,\mu m$	0.23
Environment	$u_{e(1)}$	<u>Uncertainty component from temperature difference between workpiece and instrument</u> It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.5 °C. The nominal length $L = 56\,mm$ is used. $u_{e(1)} = \Delta T \cdot (\alpha_{workpiece} - \alpha_{instrument}) \cdot L \cdot b = 0.5\,°C \times (95\times10^{-6}\,K^{-1} - 0.0\times10^{-6}\,K^{-1})$ $\times 56\,mm \times 0.7 = 1.86\,\mu m$ A U- distribution is assumed (b = 0.7).	1.86

	$u_{e(2)}$	Uncertainty component from temperature deviation from standard reference temperature for instrument The temperature deviation is assumed to the same value as the temperature variation, 0.28 °C. The nominal length $L = 56\,mm$ is used. $u_{e(2)} = \Delta T \cdot (\alpha_{instrument}) \cdot L \cdot b = 0.28°C \times (0.0 \times 10^{-6}\ K^{-1}) \times 56\,mm \times 0.7$ $= 0.00\,\mu m$ A U- distribution is assumed (b = 0.7).	0.00
	$u_{e(3)}$	Uncertainty component from temperature deviation from standard reference temperature for workpiece It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.5 °C. The nominal length $L = 56\,mm$ is used. $u_{e(2)} = \Delta T \cdot (\alpha_{workpiece}) \cdot L \cdot b = 0.5\,°C \times (95 \times 10^{-6}\ K^{-1}) \times 56\,mm \times 0.7$ $= 1.86\,\mu m$ A U- distribution is assumed (b = 0.7).	1.86
	$u_{e(4)}$	Uncertainty component from workpiece expansion coefficient uncertainty The estimated range of the thermal expansion coefficient is ± 15 · 10^{-6} K^{-1}. The nominal length $L = 56\,mm$ is used. The maximum temperature difference from the standard reference temperature from the 30 samples is used to get an uncertainty component, which cover the data for all the samples. $\Delta T_{max} = 20.63°C - 20.00°C = 0.63°C$. A U- distribution is assumed (*b = 0.7*), so the limit value is $u_{e(4)} = \Delta T_{max} \cdot \Delta\alpha \cdot L \cdot b = 0.63°C \times 15 \times 10^{-6}\ K^{-1} \times 56\,mm \times 0.7 = 0.37\,\mu m$	0.37
Procedure	u_p	Uncertainty component from measurement process This component is a type A evaluation and is estimated to follow a Gaussian distribution. No replicates are performed for the 30 samples. Instead the repeatability was evaluated based on one single sample with 5 un-filtered replicates in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0,0001 mm, $t_{0.025}$ = 2.776 with 4 degrees of freedom. It is assumed that u_p can be written as: $u_p = s \cdot \frac{t}{\sqrt{n}} = 0.1\,\mu m \cdot \frac{2.776}{\sqrt{5}} = 0.12\,\mu m$	0.12
Combined standard uncertainty	u_c	Combined standard uncertainty The combined standard uncertainty can be written as: $u_c = \sqrt{u_{r(2)}^2 + u_{rep(2)}^2 + u_w^2 + u_{e(1)}^2 + u_{e(2)}^2 + u_{e(3)}^2 + u_{e(4)}^2 + u_p^2}$ $= \sqrt{(0.20\mu m)^2 + (0.03\mu m)^2 + (0.23\mu m)^2 + (1.86\mu m)^2 + (0.00\mu m)^2 + (1.86\mu m)^2 + (0.37\mu m)^2 + (0.12\mu m)^2}$ $= 2.68\mu m$	2.68
Expanded uncertainty (k=2)	U	Expanded uncertainty The expanded uncertainty can be written as: $U = k \cdot u_c = 2 \cdot 2.68\mu m = 5.35\mu m$	5.35

5.1.1.4. *Uncorrected measurement example for Item 2 ID no. 2 before circulation*

List of the uncorrected measurement results at CGM					
Category	Measurand	Symbol	No. of measurements	Measured size [mm]	Estimate [mm]
Average, from repeated measurements	*D1*	$\overline{Y}$	5	3.4039	3.4038
				3.4034	
				3.4039	
				3.4038	
				3.4039	
Average, from repeated measurements	*R1*	$\overline{Y}$	5	0.0035	0.0035
				0.0038	
				0.0037	
				0.0033	
				0.0034	
Average. from repeated measurements	*D2*	$\overline{Y}$	5	3.3983	3.3984
				3.3987	
				3.3985	
				3.3983	
				3.3983	
Average. from repeated measurements	*R2*	$\overline{Y}$	5	0.0545	0.0550
				0.0555	
				0.0552	
				0.0550	
				0.0550	
Average. from repeated measurements	*L1*	$\overline{Y}$	5	46.3645	46.3650
				46.3662	
				46.3648	
				46.3649	
				46.3646	
Average. from repeated measurements	Ø 8 mm ring gauge. diameter	$\overline{Y}$	10	8.0015	8.0015
				8.0018	
				8.0011	
				8.0016	
				8.0015	
				8.0015	
				8.0017	
				8.0014	
				8.0016	
				8.0015	
Average. from repeated measurements	Ø 8 mm ring gauge. roundness	$\overline{Y}$	10	0.0043	0.0040
				0.0040	
				0.0035	
				0.0039	
				0.0040	
				0.0042	
				0.0041	
				0.0042	
				0.0039	
				0.0039	
Average. from repeated measurements	50 mm gauge block	$\overline{Y}$	10	50.0005	50.0002
				50.0003	
				50.0001	
				50.0005	
				50.0003	
				50.0001	
				50.0001	
				50.0005	
				50.0001	
				49.9999	

5.1.1.5. Bias budget example for Item 2 ID no. 2 before circulation

The bias budget example for Item 2 ID no. 2 before circulation is divided in five sub-budgets; the diameter D1, the roundness R1, the diameter D2, the roundness R2 and the length L1.

5.1.1.5.1. Item 2, ID no. 2, Diameter D1

Item 2, ID no. 2, Diameter D1, Detailed description of the compensation of systematic deviations			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$b_{r(1)}$	Compensation of systematic deviation due to reference artifact (ring gauge, Ø8 mm) The compensation is based on 10 repeated measurements on a ring gauge, Ø8 mm with the reference value $x = 8.0003mm$, where the measurements result in an average value of $\overline{Y} = 8.0015mm$. $b_{r(1)} = \overline{Y} - x = 8.0015mm - 8.0003mm = 1.20\mu m$	1.20
Environment	$b_{e(1)}$	Compensation of systematic deviation due to temperature (ring gauge, Ø8 mm) This systematic deviation due to the temperature of the ring gauge, Ø8 mm has been made manually using the information of the thermal expansion coefficient and the temperature. A calculation example is given below for the ring gauge, where the temperature difference is 0.6 °C (measured temperature was 20.6 °C). But the operational sign should be reversed, because a compensation of the systematic deviation due to the reference artefact is already performed ($b_{r(1)}$): $b_{e(1)} = -\Delta T \cdot (\alpha_{ringgauge}) \cdot \overline{Y} = -(20.6 - 20)°C \times (11.5 \times 10^{-6}\ K^{-1}) \times 8.0015mm = -0.06\mu m$	-0.06
	$b_{e(3)}$	Compensation of systematic deviation due to temperature (work piece) This compensation has been made manually for **each sample** using the information of the thermal expansion coefficient and the temperature. A calculation example is given below for the diameter D1, where the temperature difference is 0.1 °C (measured temperature was 20.1 °C): $b_{e(3)} = \Delta T \cdot (\alpha_{workpiece}) \cdot \overline{Y} = (20.1 - 20)°C \times (20 \times 10^{-6}\ K^{-1}) \times 3.4038mm = 0.01\mu m$	0.01
Total bias	b	Compensation of total systematic deviation due to all biases The total systematic error can be written as the summation of all the systematic errors $b = b_{r(1)} + b_{e(1)} + b_{e(3)} = 1.20\mu m + (-0.06\mu m) + 0.01\mu m = 1.15\mu m$	1.15

5.1.1.5.2. Item 2, ID no. 2, Roundness R1

Item 2, ID no. 2, Roundness R1, Detailed description of the compensation of systematic deviations			
Category	Symbol	Comments and procedure	Estimate [µm]
Total bias	b	Compensation of total systematic deviation due to all biases The total systematic error can be written as the summation of all the systematic errors $b = 0.00\mu m$	0.00

5.1.1.5.3. Item 2, ID no. 2, Diameter D2

Item 2, ID no. 2, Diameter D2, Detailed description of the compensation of systematic deviations			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$b_{r(1)}$	Compensation of systematic deviation due to reference artifact (ring gauge, Ø8 mm) The compensation is based on 10 repeated measurements on a ring gauge, Ø8 mm with the reference value $x = 8.0003mm$, where the measurements result in an average value of $\overline{Y} = 8.0015mm$. $b_{r(1)} = \overline{Y} - x = 8.0015mm - 8.0003mm = 1.20\mu m$	1.20
Environment	$b_{e(1)}$	Compensation of systematic deviation due to temperature (ring gauge, Ø8 mm) This systematic deviation due to the temperature of the ring gauge, Ø8 mm has been made manually using the information of the thermal expansion coefficient and the temperature. A calculation example is given below for the ring gauge, where the temperature difference is 0.6 °C (measured temperature was 20.6 °C). But the operational sign should be reversed, because a compensation of the systematic deviation due to the reference artefact is already performed ($b_{r(1)}$): $b_{e(1)} = -\Delta T \cdot (\alpha_{ringgauge}) \cdot \overline{Y} = -(20.6 - 20)°C \times (11.5 \times 10^{-6}\ K^{-1}) \times 8.0015mm = -0.06\mu m$	-0.06
	$b_{e(3)}$	Compensation of systematic deviation due to temperature (work piece) This compensation has been made manually for **each sample** using the information of the thermal expansion coefficient and the temperature. A calculation example is given below for the diameter D2, where the temperature difference is 0.1 °C (measured temperature was 20.1 °C): $b_{e(3)} = \Delta T \cdot (\alpha_{workpiece}) \cdot \overline{Y} = (20.1 - 20)°C \times (20 \times 10^{-6}\ K^{-1}) \times 3.3984mm = 0.01\mu m$	0.01
Total bias	b	Compensation of total systematic deviation due to all biases The total systematic error can be written as the summation of all the systematic errors $b = b_{r(1)} + b_{e(1)} + b_{e(3)} = 1.20\mu m + (-0.06\mu m) + 0.01\mu m = 1.15\mu m$	1.15

5.1.1.5.4. Item 2, ID no. 2, Roundness R2

Item 2, ID no. 2, Roundness R2, Detailed description of the compensation of systematic deviations			
Category	Symbol	Comments and procedure	Estimate [µm]
Total bias	b	Compensation of total systematic deviation due to all biases The total systematic error can be written as the summation of all the systematic errors $b = 0.00\mu m$	0.00

5.1.1.5.5. Item 2, ID no. 2, Length L1

Item 2, ID no. 2, Length L1, Detailed description of the compensation of systematic deviations			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$b_{r(2)}$	Compensation of systematic deviation due to reference artifact (gauge block, 50 mm) The compensation is based on 10 repeated measurements on a 50 mm gauge block with the reference value $x = 49.9998mm$, where the measurements result in an average value of $\overline{Y} = 50.0002mm$. $b_{r(2)} = \overline{Y} - x = 50.0002mm - 49.9998mm = 0.40\,\mu m$	0.40
Environment	$b_{e(2)}$	Compensation of systematic deviation due to temperature (gauge block, 50 mm) This systematic deviation due to the temperature of the gauge block has been made manually using the information of the thermal expansion coefficient and the temperature. A calculation example is given below for the gauge block, where the temperature difference is 0.6 °C (measured temperature was 20.6 °C). But the operational sign should be reversed, because a compensation of the systematic deviation due to the reference artefact is already performed ($b_{r(2)}$): $b_{e(2)} = -\Delta T \cdot (\alpha_{gaugeblock}) \cdot \overline{Y} = -(20.6 - 20)°C \times (11.5 \times 10^{-6}\ K^{-1}) \times 50.0002mm = -0.30\mu m$	-0.30
	$b_{e(3)}$	Compensation of systematic deviation due to temperature (work piece) This compensation has been made manually for **each sample** using the information of the thermal expansion coefficient and the temperature. A calculation example is given below for the length L1, where the temperature difference is 0.1 °C (measured temperature was 20.1 °C): $b_{e(3)} = \Delta T \cdot (\alpha_{workpiece}) \cdot \overline{Y} = (20.1 - 20)°C \times (20 \times 10^{-6}\ K^{-1}) \times 46.36501mm = 0.09\mu m$	0.09
Total bias	b	Compensation of total systematic deviation due to all biases The total systematic error can be written as the summation of all the systematic errors $b = b_{r(2)} + b_{e(2)} + b_{e(3)} = 0.40\mu m + (-0.30\mu m) + 0.09\mu m = 0.19\mu m$	0.19

5.1.1.6. Uncertainty budget example for Item 2 ID no. 2 before circulation

The uncertainty budget example for Item 2 ID no. 2 before circulation is divided in five sub-budgets; the diameter *D1*, the roundness *R1*, the diameter *D2*, the roundness *R2* and the length *L1*.

5.1.1.6.1. Item 2, ID no. 2, Diameter D1

Item 2, ID no. 2, Diameter D1, Detailed description of the procedure for each of the uncertainty contributions			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$u_{r(1)}$	Uncertainty component from ring gauge, Ø8 mm A ring gauge with a nominal diameter of Ø8 mm is used as reference. The central diameter coincides within ± 0.70 µm. The uncertainty from the certificate of the ring gauge is given with a coverage factor k =2 (95% confidence level). The standard uncertainty can be written as: $u_{r(1)} = \frac{0.70\,\mu m}{2} = 0.35\,\mu m$	0.35
Measuring instrument	$u_{rep(1)}$	Uncertainty component from repeatability on ring gauge, Ø8 mm This component is a type A evaluation and is estimated to follow a Gaussian distribution. The repeatability was evaluated based on a Ø8 mm ring gauge with 10 replicates (n = 10) in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0.0002 mm, $t_{0.025}$ = 2.262 with 9 degrees of freedom. It is assumed that $u_{rep(1)}$ can be written as: $u_{rep(1)} = s \cdot \frac{t}{\sqrt{n}} = 0.2\,\mu m \cdot \frac{2.262}{\sqrt{10}} = 0.14\mu m$	0.14
Workpiece	u_w	Uncertainty component from work piece It is assumed that the form of the work piece can be estimated based on the deviation between the maximum and minimum diameters from 5 repeated measurements for **each sample**. This component is a type B evaluation and the form is estimated to follow a rectangular distribution (b = 0.6), so it gives $u_w = form \cdot b = 0.00046 mm \times 0.6 = 0.27\,\mu m$	0.27
Environment	$u_{e(1)}$	Uncertainty component from temperature difference between workpiece and instrument It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The nominal diameter $D = 3.4\,\mathrm{mm}$ is used. $u_{e(1)} = \Delta T \cdot (\alpha_{workpiece} - \alpha_{instrument}) \cdot D \cdot b = 0.35°C \times (20\times10^{-6}\ \mathrm{K}^{-1} - 7.8\times10^{-6}\ \mathrm{K}^{-1})$ $\times 3.4\,\mathrm{mm} \times 0.7 = 0.01\,\mu m$ A U- distribution is assumed (b = 0.7).	0.01
	$u_{e(2)}$	Uncertainty component from temperature deviation from standard reference temperature for instrument It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The nominal diameter $D = 3.4\,\mathrm{mm}$ is used. $u_{e(2)} = \Delta T \cdot (\alpha_{instrument}) \cdot D \cdot b = 0.35°C \times (7.8\times10^{-6}\ \mathrm{K}^{-1}) \times 3.4\,\mathrm{mm} \times 0.7$ $= 0.01\,\mu m$ A U- distribution is assumed (b = 0.7).	0.01

	$u_{e(3)}$	Uncertainty component from temperature deviation from standard reference temperature for workpiece It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The nominal diameter $D = 3.4\,mm$ is used. $u_{e(3)} = \Delta T \cdot (\alpha_{workpiece}) \cdot D \cdot b = 0.35°C \times (20 \times 10^{-6}\ K^{-1}) \times 3.4\,mm \times 0.7$ $= 0.02\,\mu m$ A U- distribution is assumed (b = 0.7).	0.02
	$u_{e(4)}$	Uncertainty component from workpiece expansion coefficient uncertainty The estimated range of the thermal expansion coefficient is ± 1 · 10^{-6} K^{-1}. The nominal diameter $D = 3.4\,mm$ is used. The maximum temperature difference from the standard reference temperature from the 29 samples is used to get an uncertainty component, which cover the data for all the samples. $\Delta T_{max} = 20.45°C - 20.00°C = 0.45°C$. A U- distribution is assumed (*b = 0.7*), so the limit value is $u_{e(4)} = \Delta T_{max} \cdot \Delta\alpha \cdot D \cdot b = 0.45°C \times 1 \times 10^{-6}\ K^{-1} \times 3.4\,mm \times 0.7 = 0.00\,\mu m$	0.00
Procedure	u_p	Uncertainty component from measurement process This component is a type A evaluation and is estimated to follow a Gaussian distribution. 5 replicates are performed for each of the 29 samples. The repeatability was evaluated based on **each sample** with 5 replicates. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0,0002 mm, $t_{0.025}$ = 2.776 with 4 degrees of freedom. It is assumed that u_p can be written as: $u_p = s \cdot \frac{t}{\sqrt{n}} = 0.2\,\mu m \cdot \frac{2.776}{\sqrt{5}} = 0.24\,\mu m$	0.24
Combined standard uncertainty	u_c	Combined standard uncertainty The combined standard uncertainty can be written as: $u_c = \sqrt{u_{r(1)}^2 + u_{rep(1)}^2 + u_w^2 + u_{e(1)}^2 + u_{e(2)}^2 + u_{e(3)}^2 + u_{e(4)}^2 + u_p^2}$ $= \sqrt{(0.35\mu m)^2 + (0.14\mu m)^2 + (0.27\mu m)^2 + (0.01\mu m)^2 + (0.01\mu m)^2 + (0.02\mu m)^2 + (0.00\mu m)^2 + (0.24\mu m)^2}$ $= 0.52\,\mu m$	0.52
Expanded uncertainty (k=2)	U	Expanded uncertainty The expanded uncertainty can be written as: $U = k \cdot u_c = 2 \cdot 0.52\,\mu m = 1.05\,\mu m$	1.05

5.1.1.6.2. Item 2, ID no. 2, Roundness R1

Item 2, ID no. 2, Roundness R1, Detailed description of the procedure for each of the uncertainty contributions			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$u_{r(1)}$	Uncertainty component from ring gauge, Ø8 mm A ring gauge with a nominal diameter of Ø8 mm is used as reference. The central roundness coincides within ± 0.12 µm. The uncertainty from the certificate of the ring gauge is given with a coverage factor k =2 (95% confidence level). The standard uncertainty can be written as: $u_{r(1)} = \frac{0.12\mu m}{2} = 0.06\mu m$	0.06
Measuring instrument	$u_{rep(1)}$	Uncertainty component from repeatability on ring gauge, Ø8 mm This component is a type A evaluation and is estimated to follow a Gaussian distribution. The repeatability was evaluated based on a Ø8 mm ring gauge with 10 replicates (n = 10) in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0.0002 mm, $t_{0.025}$ = 2.262 with 9 degrees of freedom. It is assumed that $u_{rep(1)}$ can be written as: $u_{rep(1)} = s \cdot \frac{t}{\sqrt{n}} = 0.2\,\mu m \cdot \frac{2.262}{\sqrt{10}} = 0.14\mu m$	0.14
Workpiece	u_w	Uncertainty component from work piece It is assumed that the form of the work piece can be estimated based on the deviation between the maximum and minimum roundness from 5 repeated measurements for **each sample**. This component is a type B evaluation and the form is estimated to follow a rectangular distribution (b = 0.6), so it gives $u_w = form \cdot b = 0.00050mm \times 0.6 = 0.30\,\mu m$	0.30
Procedure	u_p	Uncertainty component from measurement process This component is a type A evaluation and is estimated to follow a Gaussian distribution. 5 replicates are performed for each of the 29 samples. The repeatability was evaluated based on **each sample** with 5 replicates. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0,0002 mm, $t_{0.025}$ = 2.776 with 4 degrees of freedom. It is assumed that u_p can be written as: $u_p = s \cdot \frac{t}{\sqrt{n}} = 0.2\,\mu m \cdot \frac{2.776}{\sqrt{5}} = 0.25\mu m$	0.25
Combined standard uncertainty	u_c	Combined standard uncertainty The combined standard uncertainty can be written as: $u_c = \sqrt{u_{r(1)}^2 + u_{rep(1)}^2 + u_w^2 + u_p^2} = \sqrt{(0.06\mu m)^2 + (0.14\mu m)^2 + (0.30\mu m)^2 + (0.25\mu m)^2}$ $= 0.42\mu m$	0.42
Expanded uncertainty (k=2)	U	Expanded uncertainty The expanded uncertainty can be written as: $U = k \cdot u_c = 2 \cdot 0.42\mu m = 0.84\mu m$	0.84

5.1.1.6.3. Item 2, ID no. 2, Diameter D2

Item 2, ID no. 2, Diameter D2, Detailed description of the procedure for each of the uncertainty contributions			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$u_{r(1)}$	Uncertainty component from ring gauge, Ø8 mm A ring gauge with a nominal diameter of Ø8 mm is used as reference. The central diameter coincides within ± 0.70 µm. The uncertainty from the certificate of the ring gauge is given with a coverage factor k =2 (95% confidence level). The standard uncertainty can be written as: $u_{r(1)} = \frac{0.70\,\mu m}{2} = 0.35\,\mu m$	0.35
Measuring instrument	$u_{rep(1)}$	Uncertainty component from repeatability on ring gauge, Ø8 mm This component is a type A evaluation and is estimated to follow a Gaussian distribution. The repeatability was evaluated based on a Ø8 mm ring gauge with 10 replicates (n = 10) in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0.0002 mm, $t_{0.025}$ = 2.262 with 9 degrees of freedom. It is assumed that $u_{rep(1)}$ can be written as: $u_{rep(1)} = s \cdot \frac{t}{\sqrt{n}} = 0.2\,\mu m \cdot \frac{2.262}{\sqrt{10}} = 0.14\,\mu m$	0.14
Workpiece	u_w	Uncertainty component from work piece It is assumed that the form of the work piece can be estimated based on the deviation between the maximum and minimum diameters from 5 repeated measurements for **each sample**. This component is a type B evaluation and the form is estimated to follow a rectangular distribution (b = 0.6), so it gives $u_w = form \cdot b = 0.00050 mm \times 0.6 = 0.30\,\mu m$	0.30
Environment	$u_{e(1)}$	Uncertainty component from temperature difference between workpiece and instrument It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The nominal diameter $D = 3.4\,\text{mm}$ is used. $u_{e(1)} = \Delta T \cdot (\alpha_{workpiece} - \alpha_{instrument}) \cdot D \cdot b = 0.35°C \times (20\times10^{-6}\ \text{K}^{-1} - 7.8\times10^{-6}\ \text{K}^{-1})$ $\times 3.4\,\text{mm} \times 0.7 = 0.01\,\mu m$ A U- distribution is assumed (b = 0.7).	0.01
	$u_{e(2)}$	Uncertainty component from temperature deviation from standard reference temperature for instrument It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The nominal diameter $D = 3.4\,\text{mm}$ is used. $u_{e(2)} = \Delta T \cdot (\alpha_{instrument}) \cdot D \cdot b = 0.35°C \times (7.8\times10^{-6}\ \text{K}^{-1}) \times 3.4\,\text{mm} \times 0.7$ $= 0.01\,\mu m$ A U- distribution is assumed (b = 0.7).	0.01
	$u_{e(3)}$	Uncertainty component from temperature deviation from standard reference temperature for workpiece It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The nominal diameter $D = 3.4\,\text{mm}$ is used. $u_{e(3)} = \Delta T \cdot (\alpha_{workpiece}) \cdot D \cdot b = 0.35°C \times (20\times10^{-6}\ \text{K}^{-1}) \times 3.4\,\text{mm} \times 0.7$ $= 0.02\,\mu m$ A U- distribution is assumed (b = 0.7).	0.02

	$u_{e(4)}$	Uncertainty component from workpiece expansion coefficient uncertainty The estimated range of the thermal expansion coefficient is ± 1 · 10^{-6} K^{-1}. The nominal diameter $D = 3.4\,mm$ is used. The maximum temperature difference from the standard reference temperature from the 29 samples is used to get an uncertainty component, which cover the data for all the samples. $\Delta T_{max} = 20.45°C - 20.00°C = 0.45°C$. A U- distribution is assumed (*b = 0.7*), so the limit value is $u_{e(4)} = \Delta T_{max} \cdot \Delta\alpha \cdot D \cdot b = 0.45°C \times 1 \times 10^{-6}\ K^{-1} \times 3.4\,mm \times 0.7 = 0.00\,\mu m$	0.00
Procedure	u_p	Uncertainty component from measurement process This component is a type A evaluation and is estimated to follow a Gaussian distribution. 5 replicates are performed for each of the 29 samples. The repeatability was evaluated based on **each sample** with 5 replicates. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0,0002 mm, $t_{0.025}$ = 2.776 with 4 degrees of freedom. It is assumed that u_p can be written as: $u_p = s \cdot \frac{t}{\sqrt{n}} = 0.2\,\mu m \cdot \frac{2.776}{\sqrt{5}} = 0.21\,\mu m$	0.21
Combined standard uncertainty	u_c	Combined standard uncertainty The combined standard uncertainty can be written as: $u_c = \sqrt{u_{r(1)}^2 + u_{rep(1)}^2 + u_w^2 + u_{e(1)}^2 + u_{e(2)}^2 + u_{e(3)}^2 + u_{e(4)}^2 + u_p^2}$ $= \sqrt{(0.35\mu m)^2 + (0.14\mu m)^2 + (0.30\mu m)^2 + (0.01\mu m)^2 + (0.01\mu m)^2 + (0.02\mu m)^2 + (0.00\mu m)^2 + (0.21\mu m)^2}$ $= 0.53\mu m$	0.53
Expanded uncertainty (k=2)	U	Expanded uncertainty The expanded uncertainty can be written as: $U = k \cdot u_c = 2 \cdot 0.53\mu m = 1.06\mu m$	1.06

5.1.1.6.4. Item 2, ID no. 2, Roundness R2

Item 2, ID no. 2, Roundness R2, Detailed description of the procedure for each of the uncertainty contributions			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$u_{r(1)}$	Uncertainty component from ring gauge, Ø8 mm A ring gauge with a nominal diameter of Ø8 mm is used as reference. The central roundness coincides within ± 0.12 µm. The uncertainty from the certificate of the ring gauge is given with a coverage factor k =2 (95% confidence level). The standard uncertainty can be written as: $u_{r(1)} = \frac{0.12\,\mu m}{2} = 0.06\,\mu m$	0.06
Measuring instrument	$u_{rep(1)}$	Uncertainty component from repeatability on ring gauge, Ø8 mm This component is a type A evaluation and is estimated to follow a Gaussian distribution. The repeatability was evaluated based on a Ø8 mm ring gauge with 10 replicates (n = 10) in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0.0002 mm, $t_{0.025}$ = 2.262 with 9 degrees of freedom. It is assumed that $u_{rep(1)}$ can be written as: $u_{rep(1)} = s \cdot \frac{t}{\sqrt{n}} = 0.2\,\mu m \cdot \frac{2.262}{\sqrt{10}} = 0.14\mu m$	0.14
Workpiece	u_w	Uncertainty component from work piece It is assumed that the form of the work piece can be estimated based on the deviation between the maximum and minimum roundness from 5 repeated measurements for **each sample**. This component is a type B evaluation and the form is estimated to follow a rectangular distribution (b = 0.6), so it gives $u_w = form \cdot b = 0.00106 mm \times 0.6 = 0.64\,\mu m$	0.64
Procedure	u_p	Uncertainty component from measurement process This component is a type A evaluation and is estimated to follow a Gaussian distribution. 5 replicates are performed for each of the 29 samples. The repeatability was evaluated based on **each sample** with 5 replicates. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0,0004 mm, $t_{0.025}$ = 2.776 with 4 degrees of freedom. It is assumed that u_p can be written as: $u_p = s \cdot \frac{t}{\sqrt{n}} = 0.4\,\mu m \cdot \frac{2.776}{\sqrt{5}} = 0.50\mu m$	0.50
Combined standard uncertainty	u_c	Combined standard uncertainty The combined standard uncertainty can be written as: $u_c = \sqrt{u_{r(1)}^2 + u_{rep(1)}^2 + u_w^2 + u_p^2} = \sqrt{(0.06\mu m)^2 + (0.14\mu m)^2 + (0.64\mu m)^2 + (0.50\mu m)^2}$ $= 0.83\mu m$	0.83
Expanded uncertainty (k=2)	U	Expanded uncertainty The expanded uncertainty can be written as: $U = k \cdot u_c = 2 \cdot 0.83\mu m = 1.65\mu m$	1.65

5.1.1.6.5. Item 2, ID no. 2, Length L1

Item 2, ID no. 2, Length L1, Detailed description of the procedure for each of the uncertainty contributions			
Category	Symbol	Comments and procedure	Estimate [µm]
Reference standard	$u_{r(2)}$	Uncertainty component from gauge block, 50 mm A gauge block with a nominal length of 50 mm is used as reference. The central length coincides within ± 0.10 µm. The uncertainty from the certificate of the gauge block is given with a coverage factor k =2 (95% confidence level). The standard uncertainty can be written as: $u_{r(2)} = \frac{0.12\,\mu m}{2} = 0.06\,\mu m$	0.06
Measuring instrument	$u_{rep(2)}$	Uncertainty component from repeatability on gauge block, 50 mm This component is a type A evaluation and is estimated to follow a Gaussian distribution. The repeatability was evaluated based on a 50 mm gauge block with 10 replicates (n = 10) in order to determine the contribution to the uncertainty due to repeatability. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0.0002 mm, $t_{0.025}$ = 2.262 with 9 degrees of freedom. It is assumed that $u_{rep(2)}$ can be written as: $u_{rep(2)} = s \cdot \frac{t}{\sqrt{n}} = 0.2\,\mu m \cdot \frac{2.262}{\sqrt{10}} = 0.14\,\mu m$	0.14
Workpiece	u_w	Uncertainty component from work piece Generally two cases contribute to the form of the work piece; (1) the position of the center axis of datum A (axis of outside cylinder), which influences on the center position and (2) the flatness of datum B. Instead it is assumed that the form can be estimated based on the deviation between the maximum and minimum lengths from 5 repeated measurements for **each sample**, which cover the two contributes ((1) and (2)) to the form. This component is a type B evaluation and the form is estimated to follow a rectangular distribution (b = 0.6), so it gives $u_w = form \cdot b = 0.00170 mm \times 0.6 = 1.02\,\mu m$	1.02
Environment	$u_{e(1)}$	Uncertainty component from temperature difference between workpiece and instrument It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The nominal length $L = 46\,mm$ is used. $u_{e(1)} = \Delta T \cdot (\alpha_{workpiece} - \alpha_{instrument}) \cdot L \cdot b = 0.35°C \times (20\times10^{-6}\ K^{-1} - 7.8\times10^{-6}\ K^{-1})$ $\times 46\,mm \times 0.7 = 0.14\,\mu m$ A U- distribution is assumed (b = 0.7).	0.14
	$u_{e(2)}$	Uncertainty component from temperature deviation from standard reference temperature for instrument It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The nominal length $L = 46\,mm$ is used. $u_{e(2)} = \Delta T \cdot (\alpha_{instrument}) \cdot L \cdot b = 0.35°C \times (7.8\times10^{-6}\ K^{-1}) \times 46\,mm \times 0.7$ $= 0.09\,\mu m$ A U- distribution is assumed (b = 0.7).	0.09

	$u_{e(3)}$	Uncertainty component from temperature deviation from standard reference temperature for workpiece It is assumed that the combined uncertainty of temperature sensor and that coming from the fact that temperature is not measured inside the item amounts to 0.35 °C. The nominal length $L = 46\,\text{mm}$ is used. $u_{e(3)} = \Delta T \cdot (\alpha_{workpiece}) \cdot L \cdot b = 0.35°C \times (20 \times 10^{-6}\ \text{K}^{-1}) \times 46\,\text{mm} \times 0.7$ $= 0.23\,\mu m$ A U- distribution is assumed (b = 0.7).	0.23
	$u_{e(4)}$	Uncertainty component from workpiece expansion coefficient uncertainty The estimated range of the thermal expansion coefficient is ± 1 · 10^{-6} K^{-1}. The nominal length $L = 46\,\text{mm}$ is used. The maximum temperature difference from the standard reference temperature from the 29 samples is used to get an uncertainty component, which cover the data for all the samples. $\Delta T_{\max} = 20.45°C - 20.00°C = 0.45°C$. A U- distribution is assumed (*b = 0.7*), so the limit value is $u_{e(4)} = \Delta T_{\max} \cdot \Delta\alpha \cdot L \cdot b = 0.45°C \times 1 \times 10^{-6}\ \text{K}^{-1} \times 46\,\text{mm} \times 0.7 = 0.01\,\mu m$	0.01
Procedure	u_p	Uncertainty component from measurement process This component is a type A evaluation and is estimated to follow a Gaussian distribution. 5 replicates are performed for each of the 29 samples. The repeatability was evaluated based on **each sample** with 5 replicates. A two-sided t-test is assumed at 95 % confidence level and α = 0.05. Since s = 0,0007 mm, $t_{0.025}$ = 2.776 with 4 degrees of freedom. It is assumed that u_p can be written as: $u_p = s \cdot \frac{t}{\sqrt{n}} = 0.7\,\mu m \cdot \frac{2.776}{\sqrt{5}} = 0.86\,\mu m$	0.86
Combined standard uncertainty	u_c	Combined standard uncertainty The combined standard uncertainty can be written as: $u_c = \sqrt{u_{r(2)}^2 + u_{rep(2)}^2 + u_w^2 + u_{e(1)}^2 + u_{e(2)}^2 + u_{e(3)}^2 + u_{e(4)}^2 + u_p^2}$ $= \sqrt{(0.06\mu m)^2 + (0.14\mu m)^2 + (1.02\mu m)^2 + (0.14\mu m)^2 + (0.09\mu m)^2 + (0.23\mu m)^2 + (0.01\mu m)^2 + (0.87\mu m)^2}$ $= 1.37\,\mu m$	1.37
Expanded uncertainty (k=2)	U	Expanded uncertainty The expanded uncertainty can be written as: $U = k \cdot u_c = 2 \cdot 1.37\,\mu m = 2.74\,\mu m$	2.74

5.1.1.7. Example on the measurement protocol for Item 1

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================================================================================

                        CONTROL DATA LIST   ZEISS  UMESS

WORKPIECE NAME:   LEGO 1x8 brick program b
FILE NAME:  CNCCT_______8B
CONTROL DATA LINES:  596             NOMINAL LINES :    0
================================================================================
    |     X     |     Y     |     Z     |             |      |      |      |      |
 NO |--------------------------------|   Function   |  SC2 |  SC1 |  PCN |  CCN |  ADR
    |               Dialog            |             |      |      |      |      |
 NO |    Nominal     | U.Tol    L.Tol  |   Function   |  SC2 |  SC1 |  PCN |  CCN |
 NO |            Identification      |   Function   |  SC2 |  SC1 |  PCN |  CCN |  ADR
================================================================================
   1 LEGO brick 1x8                      RECORD HEAD      0      8  1610  1650
   2 n/a [red]                            DL R HEAD       0      0  9911     0
   3 CIA-CT                               DL R HEAD       0      0  9911     0
   4 CIA-CT                               DL R HEAD       0      0  9911     0
   5 intercomparis.                       DL R HEAD       0      0  9911     0
   6 |                                    DL R HEAD       0      0  9911     0
   7                                     LDL REC HEAD     0      0  9919     0
   8        1        15        1       0 PRB-CONF-LIS     0      1  6509  3090
   9 AB                                  TIME STAMP       0      1  1618     0
  10   95.00000                          TEMP COMP        0      1  6511  3111
  11 Thermal exp. coeff.                 TEXT             0      2  1676     0
  12 used: 95  K-1*10-6                  LDL TEXT         0      0  9919     0
  13         15                          WPOS F DISK      0      1  MMMM  MMMM
  14                                     WPOS TO WSYS     0      0  1713  1640     1
  15 --------------------                TEXT             0      2  1676     0
  16 ------------                        LDL TEXT         0      0  9919     0
  17 Rough alignment                     TEXT             0      1  1676     0
  18 --------------------                TEXT             0      2  1676     0
  19 ------------                        LDL TEXT         0      0  9919     0
  20 spatial/primary alig                TEXT             0      3  1676     0
  21 nment on upper surfa                 DL TEXT         0      0  9911     0
  22 ce:                                 LDL TEXT         0      0  9919     0
  23    4.00000     2.95000   220.03080 I-POS             0  11110     0  1101
  24    4.00000     2.95000     5.00000 I-POS             0  11110     0  1101

  25                                     SURFACE          0      0  1103  1410
  26    4.00000     2.95000     0.51770 PROBING    -Z     0  11107     0  1103
  27    4.00000     2.95000     5.00000 I-POS             0  11110     0  1101
  28    4.00000    -2.95000     5.00000 I-POS             0  11110     0  1101
  29    4.00000    -2.95000     0.50710 PROBING    -Z     0  11107     0  1103
  30    3.98510    -1.66910     5.00000 I-POS             0  11110     0  1101
  31   52.00000    -2.95000     5.00000 I-POS             0  11110     0  1101
  32   52.00000    -2.95000     0.51860 PROBING    -Z     0  11107     0  1103
  33   52.00000    -2.95000     5.00000 I-POS             0  11110     0  1101
  34   52.00000     2.95000     5.00000 I-POS             0  11110     0  1101
  35   52.00000     2.95000     0.51700 PROBING    -Z     0  11107     0  1103
  36   52.00000     2.95000     5.00000 I-POS             0  11110     0  1101

  37                                     N POINT TERM     3      0  1191  1420     2
  38                                     ROTATE SPACE     0      0  1706  1640     3
  39                                     ZERO POINT       0      0  1701  1640     4
  40   59.98760     2.95000     5.00000 I POS             0  11110     0  1101
  41   60.67900     0.00000     5.00000 I POS             0  11110     0  1101
  42   60.67520     0.00000     1.92940 I-POS             0  11110     0  1101
  43   60.67480     0.00000     1.00000 I-POS             0  11110     0  1101
  44                                     TEXT             0      1  1676     0
  45 Top no. 8 - right si                TEXT             0      2  1676     0
```

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=================================================================================
DATE :  09/02/13    W-NAME: LEGO 1x8 brick program b             PAGE : -  2   -
     |     X     |      Y     |      Z    |             |      |      |      |      |
 NO  |----------------------------------- |  Function   |  SC2 |  SC1 |  PCN |  CCN |  ADR
     |                Dialog              |             |      |      |      |      |
 NO  |    Nominal      | U.Tol   |  L.Tol |  Function   |  SC2 |  SC1 |  PCN |  CCN |
 NO  |           Identification           |  Function   |  SC2 |  SC1 |  PCN |  CCN |  ADR
=================================================================================
  46 de:                                 LDL TEXT        0      0  9919     0

  47                                     CIRCLE          0      0  1104  1410
  48 43   1   1   1    1.00000   1.00000 SCANNING MOD    1      7  1530  1330
  49      2    3    1 $$ 0.00000 1.00000 SC DESTCODE     2      1  9911  1911
  50             0     3.00000   0.00000 SCA CLAM MOD    5      1  9911  1911
  51             0     0.00000   0.00000 SCA TARG WIN    7      1  9919  1919
  52 43   1   1   1    1.00000   0.80000 SCANNING MOD    1      7  1530  1330
  53      2    3    1 $$ 0.00000 1.00000 SC DESTCODE     2      1  9911  1911
  54             0     3.00000   0.00000 SCA CLAM MOD    5      1  9911  1911
  55             0     0.00000   0.00000 SCA TARG WIN    7      1  9919  1919
  56 0.02000    43     0     0     0 3   1 SCANNING      4      4  1531  1331
  57    58.24060     0.25142     1.00000  DL SC_SPT      0  11109     0  1911
  58    58.24060     0.25136     1.00000  DL SC_IPT      0  11109     0  1911
  59     0.80000     0.00000     0.00000 LDL SC_SPEED    0      0     0  1919

  60                                     N POINT TERM    3      0  1191  1420     5
  61                                     XYZ             0      0  1262     0
  62    60.82360     0.00000     1.00000 I-POS           0  11110     0  1101
  63    60.82850     0.00000     5.00000 I-POS           0  11110     0  1101
  64     3.87150     0.00000     5.00000 I-POS           0  11110     0  1101
  65                                     TEXT            0      1  1676     0
  66 Top no. 1 - left sid                TEXT            0      2  1676     0
  67 e:                                  LDL TEXT        0      0  9919     0
  68     3.86630     0.00000     1.00000 I-POS           0  11110     0  1101

  69                                     CIRCLE          0      0  1104  1410
  70 43   1   1   1    1.00000   0.80000 SCANNING MOD    1      7  1530  1330
  71      2    3    1 $$ 0.00000 1.00000 SC DESTCODE     2      1  9911  1911
  72             0     3.00000   0.00000 SCA CLAM MOD    5      1  9911  1911
  73             0     0.00000   0.00000 SCA TARG WIN    7      1  9919  1919
  74 0.02000    43     0     0     0 3   1 SCANNING      4      4  1531  1331
  75     2.39770     0.36893     1.00000  DL SC_SPT      0  11109     0  1911
  76     2.39770     0.36896     1.00000  DL SC_IPT      0  11109     0  1911
  77     0.80000     0.00000     0.00000 LDL SC_SPEED    0      0     0  1919

  78                                     N POINT TERM    3      0  1191  1420     6
  79                                     XYZ             0      0  1262     0
  80     3.59140     0.00000     1.00000 I POS           0  11110     0  1101
  81     3.59532     0.53394     4.32510 I POS           0  11110     0  1101
  82             3   360.27358           RO PLANE        0      1  1702  1640     7
  83                                     ZERO POINT      0      0  1701  1640     8
  84 Plane/secondary alig                TEXT            0      3  1676     0
  85 nment done between t                 DL TEXT        0      0  9911     0
  86 he two circles.                     LDL TEXT        0      0  9919     0
  87 Zeropoint in X/terti                TEXT            0      4  1676     0
  88 ary alignment done a                 DL TEXT        0      0  9911     0
  89 t the left circle no                 DL TEXT        0      0  9911     0
  90 . 1                                 LDL TEXT        0      0  9919     0
  91                                     W-POS           0      0  1708  1610
  92 (W-POS stored)                      TEXT            0      1  1676     0
  93                                     TEXT            0      1  1676     0
  94 --------------------                TEXT            0      2  1676     0
```

DATE : 09/02/13 W-NAME: LEGO 1x8 brick program b PAGE : - 3 -

NO	X / Nominal	Y / U.Tol	Z / L.Tol	Function	SC2	SC1	PCN	CCN	ADR
NO	Dialog			Function	SC2	SC1	PCN	CCN	
NO	Identification			Function	SC2	SC1	PCN	CCN	ADR
95	------------			LDL TEXT	0	0	9919	0	
96	Fine alignment			TEXT	0	1	1676	0	
97	--------------------			TEXT	0	2	1676	0	
98	------------			LDL TEXT	0	0	9919	0	
99	-3.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
100				SURFACE	0	0	1103	1410	
101	-3.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
102	-3.00000	2.95000	5.00000	I-POS	0	11110	0	1101	
103	3.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
104	3.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
105	3.00000	-2.95000	5.00000	I-POS	0	11110	0	1101	
106	3.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
107	3.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
108	4.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
109	4.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
110	5.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
111	5.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
112	5.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
113	3.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
114	3.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
115	4.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
116	4.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
117	5.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
118	5.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
119	5.00000	-2.95000	5.00000	I-POS	0	11110	0	1101	
120	11.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
121	11.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
122	12.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
123	12.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
124	13.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
125	13.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
126	13.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
127	11.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
128	11.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
129	12.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
130	12.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
131	13.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
132	13.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
133	13.00000	-2.95000	5.00000	I-POS	0	11110	0	1101	
134	19.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
135	19.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
136	20.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
137	20.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
138	21.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
139	21.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
140	21.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
141	19.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
142	19.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
143	20.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
144	20.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
145	21.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
146	21.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	

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NO	X	Y	Z	Function	SC2	SC1	PCN	CCN	ADR
NO	Dialog			Function	SC2	SC1	PCN	CCN	
NO	Nominal	U.Tol	L.Tol	Function	SC2	SC1	PCN	CCN	
NO	Identification			Function	SC2	SC1	PCN	CCN	ADR
147	21.00000	-2.95000	5.00000	I-POS	0	11110	0	1101	
148	27.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
149	27.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
150	28.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
151	28.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
152	29.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
153	29.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
154	29.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
155	27.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
156	27.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
157	28.00000	-2.95000	5.00000	I-POS	0	11110	0	1101	
158	28.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
159	29.00000	-2.95000	5.00000	I-POS	0	11110	0	1101	
160	29.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
161	29.00000	-2.95000	5.00000	I-POS	0	11110	0	1101	
162	35.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
163	35.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
164	36.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
165	36.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
166	37.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
167	37.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
168	37.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
169	35.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
170	35.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
171	36.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
172	36.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
173	37.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
174	37.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
175	37.00000	-2.95000	5.00000	I-POS	0	11110	0	1101	
176	43.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
177	43.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
178	44.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
179	44.00000	2.95000	0.00000	POSITION P Z	8	11107	1511	1113	
180	45.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
181	45.00000	2.95000	0.00000	POSITION P Z	8	11107	1511	1113	
182	45.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
183	43.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
184	43.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
185	44.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
186	44.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
187	45.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
188	45.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
189	45.00000	-2.95000	5.00000	I-POS	0	11110	0	1101	
190	51.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
191	51.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
192	52.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
193	52.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
194	53.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
195	53.00000	2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
196	53.00000	2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
197	51.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	
198	51.00000	-2.95000	0.00000	POSITION P-Z	8	11107	1511	1113	
199	52.00000	-2.95000	5.00000	POSITION IPT	8	11110	1511	1111	

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================================================================================
DATE :   09/02/13    W-NAME: LEGO 1x8 brick program b              PAGE : -  5   -
    |      X      |      Y      |      Z      |            |      |      |      |      |
 NO |-------------------------------------------|  Function  | SC2  | SC1  | PCN  | CCN  | ADR
    |               Dialog                      |            |      |      |      |      |
 NO |    Nominal       | U.Tol    | L.Tol       |  Function  | SC2  | SC1  | PCN  | CCN  |
 NO |           Identification                  |  Function  | SC2  | SC1  | PCN  | CCN  | ADR
================================================================================
 200   52.00000   -2.95000    0.00000 POSITION P-Z     8 11107  1511  1113
 201   53.00000   -2.95000    5.00000 I-POS            0 11110     0  1101
 202   53.00000   -2.95000    0.00000 POSITION P-Z     8 11107  1511  1113
 203   53.00000   -2.95000    5.00000 I-POS            0 11110     0  1101
 204   59.00000    2.95000    5.00000 POSITION IPT     8 11110  1511  1111
 205   59.00000    2.95000    0.00000 POSITION P-Z     8 11107  1511  1113
 206   59.00000    2.95000    5.00000 I-POS            0 11110     0  1101
 207   59.00000   -2.95000    5.00000 POSITION IPT     8 11110  1511  1111
 208   59.00000   -2.95000    0.00000 POSITION P-Z     8 11107  1511  1113
 209   59.00000   -2.95000    5.00000 I-POS            0 11110     0  1101

 210                                  N POINT TERM     3     0  1191  1420     9
 211       0        0        0      0 GDT FLAT         0     2  1402     0    10
 212     3                            PARAM            2     0  9981     0
 213   8224                           PARAM            7     0  9981     0
 214      0.00000                     PARAM           55     0  9981     0
 215 Up. surf.                        PARAM TXT       20     0  9982     0
 216    9                             PARAM            3     0  9981     0
 217                                  GDT END          0     0  9983     0
 218 --------------------             TEXT             0     4  1676     0
 219 --------------------              DL TEXT         0     0  9911     0
 220 --------------------              DL TEXT         0     0  9911     0
 221 -----------------                LDL TEXT         0     0  9919     0
 222   2 113    0    9    3  -2    8    1 GDT PLOT     0     3  1470     0
 223 STAFPCZ_EBEN_U                    DL GDT PLOT     0     0  9911     0
 224     up.sur     0.07820       500 LDL GDT PLOT     0     0  9919     0
 225                                  NEW GRAPHIC      0     0  1652     0
 226                                  ROTATE SPACE     0     0  1706  1640    11
 227                                  ZERO POINT       0     0  1701  1640    12
 228   60.00000    0.00000    1.00000 POSITION IPT    12 11110  1511  1111

 229                                  CIRCLE           0     0  1104  1410
 230 33  2  1  1   1.00000   0.80000  SCANNING MOD     1     7  1530  1330
 231          0    3.00000    0.00000 SCA CLAM MOD     5     1  9911  1911
 232          0    0.00000    0.00000 SCA TARG WIN     7     1  9919  1919
 233 33  2  1  1   1.00000   0.50000  SCANNING MOD     1     7  1530  1330
 234          0    3.00000    0.00000 SCA CLAM MOD     5     1  9911  1911
 235          0    0.00000    0.00000 SCA TARG WIN     7     1  9919  1919
 236 0.01000   33     0     0    0 3  0 SCANNING      12     4  1531  1331
 237   56.00000    0.00000    1.00000  DL SC_MPT       0 11109     0  1911
 238    0.00000  450.00000    0.00000  DL SC_ANG       0     0     0  1911
 239    0.50000    4.90000    0.00000 LDL SC_SPEED     0     0     0  1919
 240   55.97555    4.62417    0.98243 I-POS            0 11110     0  1101
 241   55.99107    4.64016    6.15904 I-POS            0 11110     0  1101

 242                                  N POINT TERM     3     0  1191  1420    13
 243                                  XYZ              0     0  1262     0
 244    4.47687    4.39578    6.22921 I-POS            0 11110     0  1101
 245    4.00000    0.00000    1.00000 POSITION IPT    12 11110  1511  1111

 246                                  CIRCLE           0     0  1104  1410
 247 33  2  1  1   1.00000   0.50000  SCANNING MOD     1     7  1530  1330
 248          0    3.00000    0.00000 SCA CLAM MOD     5     1  9911  1911
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================================================================================
DATE :  09/02/13   W-NAME: LEGO 1x8 brick program b             PAGE : -  6   -
       |    X      |     Y      |     Z      |            |     |     |     |     |
 NO    |------------------------------------|  Function  | SC2 | SC1 | PCN | CCN | ADR
       |           Dialog                   |            |     |     |     |     |
 NO    |   Nominal       | U.Tol    | L.Tol  |  Function  | SC2 | SC1 | PCN | CCN |
 NO    |           Identification           |  Function  | SC2 | SC1 | PCN | CCN | ADR
================================================================================
 249          0      0.00000     0.00000 SCA TARG WIN      7     1  9919  1919
 250 0.01000    33     0     0     0 3   0 SCANNING       12     4  1531  1331
 251     0.00000     0.00000     1.00000  DL SC_MPT        0 11109     0  1911
 252     0.00000   450.00000     0.00000  DL SC_ANG        0     0     0  1911
 253     0.50000     4.90000     0.00000 LDL SC_SPEED      0     0     0  1919
 254    -0.02496     5.52349     0.97940 I-POS             0 11110     0  1101
 255    -0.01858     5.54382     7.22176 I-POS             0 11110     0  1101

 256                                     N POINT TERM      3     0  1191  1420   14
 257                                     XYZ               0     0  1262     0
 258          3  360.27353               RO PLANE          0     1  1702  1640   15
 259                                     ZERO POINT        0     0  1701  1640   16
 260                                     W-POS             0     0  1708  1610
 261 (W-POS stored)                      TEXT              0     1  1676     0
 262 --------------------                TEXT              0     3  1676     0
 263 ------------- ALIGNM                DL TEXT           0     0  9911     0
 264 ENT FINISHED                        LDL TEXT          0     0  9919     0
 265                                     TEXT              0     1  1676     0
 266 Top no. 1                           TEXT              0     1  1676     0
 267     3.64986     5.56277     7.22842 I-POS             0 11110     0  1101
 268     4.00000     0.00000     1.00000 POSITION IPT     16 11110  1511  1111

 269                                     CIRCLE            0     0  1104  1410
 270 33   2   1   1    1.00000    0.50000  SCANNING MOD    1     7  1530  1330
 271          0      3.00000     0.00000 SCA CLAM MOD      5     1  9911  1911
 272          0      0.00000     0.00000 SCA TARG WIN      7     1  9919  1919
 273 0.01000    33     0     0     0 3   0 SCANNING       16     4  1531  1331
 274     0.00000     0.00000     1.00000  DL SC_MPT        0 11109     0  1911
 275     0.00000   450.00000     0.00000  DL SC_ANG        0     0     0  1911
 276     0.50000     4.90000     0.00000 LDL SC_SPEED      0     0     0  1919

 277                                     N POINT TERM      3     0  1191  1420   17
 278                                     XYZ               0     0  1262     0
 279   0 114   0  17    3    1    8    1 GDT PLOT          0     3  1470     0
 280 STAFPCZ_RUND_U                       DL GDT PLOT       0     0  9911     0
 281     No.  8      0.00470        5000 LDL GDT PLOT      0     0  9919     0
 282                                     NEW GRAPHIC       0     0  1652     0
 283     0.00870     4.76031     0.99406 I-POS             0 11110     0  1101
 284    -0.00367     4.77269     4.60498 I-POS             0 11110     0  1101
 285    60.23720     3.26606     4.88819 I-POS             0 11110     0  1101
 286    62.00000     0.00000     1.00000 POSITION IPT     16 11110  1511  1111
 287 Top no. 8                           TEXT              0     1  1676     0

 288                                     CIRCLE            0     0  1104  1410
 289 33   2   1   1    1.00000    0.50000  SCANNING MOD    1     7  1530  1330
 290          0      3.00000     0.00000 SCA CLAM MOD      5     1  9911  1911
 291          0      0.00000     0.00000 SCA TARG WIN      7     1  9919  1919
 292 0.01000    33     0     0     0 3   0 SCANNING       16     4  1531  1331
 293    56.00000     0.00000     1.00000  DL SC_MPT        0 11109     0  1911
 294     0.00000   450.00000     0.00000  DL SC_ANG        0     0     0  1911
 295     0.50000     4.90000     0.00000 LDL SC_SPEED      0     0     0  1919
 296    55.98431     6.18675     0.98902 I-POS             0 11110     0  1101
 297    55.99243     6.20221     5.99805 I-POS             0 11110     0  1101
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================================================================================
DATE :  09/02/13   W-NAME: LEGO 1x8 brick program b              PAGE : -  7   -
     |     X      |     Y      |     Z      |             |     |     |     |     |
 NO  |------------------------------------|  Function   | SC2 | SC1 | PCN | CCN | ADR
     |            Dialog                  |             |     |     |     |     |
 NO  |    Nominal      | U.Tol   | L.Tol   |  Function   | SC2 | SC1 | PCN | CCN |
 NO  |          Identification            |  Function   | SC2 | SC1 | PCN | CCN | ADR
================================================================================

 298                                        N POINT TERM     3      0  1191  1420    18
 299                                        XYZ              0      0  1262     0
 300   0 114    0  18    3    1    8    1  GDT PLOT         0      3  1470     0
 301 STAFPCZ_RUND_U                          DL GDT PLOT     0      0  9911     0
 302      No. 8       0.00470         5000 LDL GDT PLOT     0      0  9919     0
 303                                        NEW GRAPHIC      0      0  1652     0
 304                                        POLAR            0      0  1203     0    19
 305 --------------------                   TEXT             0      4  1676     0
 306 --------------------                    DL TEXT         0      0  9911     0
 307 --------------------                    DL TEXT         0      0  9911     0
 308 -----------------                      LDL TEXT         0      0  9919     0
 309 Top no. 4 - with inl                   TEXT             0      2  1676     0
 310 et on top:                             LDL TEXT         0      0  9919     0
 311   27.92898     6.06847     6.03770 I-POS            0  11110     0  1101
 312   28.00000     0.00000     1.00000 POSITION IPT    16  11110  1511  1111

 313                                        POINT FILE       0      0  1100  1410
 314 33   2   1   1     1.00000    0.50000 SCANNING MOD     1      7  1530  1330
 315            0     3.00000     0.00000 SCA CLAM MOD     5      1  9911  1911
 316            0     0.00000     0.00000 SCA TARG WIN     7      1  9919  1919
 317 0.01000    33      0     0     0 3   0 SCANNING        16      4  1531  1331
 318   24.00000     0.00000     1.00000  DL SC_MPT       0  11109     0  1911
 319    0.00000   450.00000     0.00000  DL SC_ANG       0      0     0  1911
 320    0.50000     4.90000     0.00000 LDL SC_SPEED     0      0     0  1919

 321   0 PKTN04        U                   FILE TERMIN      0      1  1191  1420
 322   23.98509     4.82508     0.99383 I-POS            0  11110     0  1101
 323   26.90931     4.84804     3.78217 I-POS            0  11110     0  1101

 324                                        CIRCLE           0      0  1104  1410
 325   0 PKTN04        U                   RECALL FILE      0      1  1305     0

 326                                        ZPT RECALL       3      0  1192   430    20
 327                                        XYZ              0      0  1262     0
 328                                        POLAR            0      0  1203     0    21
 329       0         0         0         0 GDT ROUND        0      2  1403     0    22
 330      3                                 PARAM            2      0  9981     0
 331   8224                                 PARAM            7      0  9981     0
 332       0.00000                          PARAM           55      0  9981     0
 333                                        PARAM TXT       20      0  9982     0
 334   20                                   PARAM            3      1  9981     0
 335                                        GDT END          0      0  9983     0
 336 --------------------                   TEXT             0      2  1676     0
 337 ------------                           LDL TEXT         0      0  9919     0
 338   0 114    0  20    3    1    8    1  GDT PLOT         0      3  1470     0
 339 STAFPCZ_RUND_U                          DL GDT PLOT     0      0  9911     0
 340      NO.4        0.00530         5000 LDL GDT PLOT     0      0  9919     0
 341                                        NEW GRAPHIC      0      0  1652     0
 342 Top no. 4 -  WITH GA                   TEXT             0      2  1676     0
 343 USS FILTER - 150                       LDL TEXT         0      0  9919     0
 344   1    1    1    0    1    0    0    0 FILTER MOD1      0      1  1185     0
```

```
================================================================================
DATE :  09/02/13   W-NAME: LEGO 1x8 brick program b                PAGE : -  8   -
     |      X      |      Y      |      Z      |            |     |     |     |     |
 NO  |-------------------------------------------| Function   | SC2 | SC1 | PCN | CCN | ADR
     |              Dialog                       |            |     |     |     |     |
 NO  |   Nominal        | U.Tol    | L.Tol       | Function   | SC2 | SC1 | PCN | CCN |
 NO  |            Identification                 | Function   | SC2 | SC1 | PCN | CCN | ADR
================================================================================
 345                                  CIRCLE          0     0  1104  1410
 346   0 PKTN04        U              RECALL FILE     0     1  1305     0
 347                                  ZPT RECALL      3     2  1192   430    23

 348 0.00000    0     0  150    0 0   0 LDL FILTER1   0     0  9919     0
 349   0 114    0  23    3    1    8    1 GDT PLOT    0     3  1470     0
 350 STAFPCZ_RUND_U                    DL GDT PLOT    0     0  9911     0
 351     NO. 4     0.00500        5000 LDL GDT PLOT   0     0  9919     0
 352                                  XYZ             0     0  1262     0
 353                                  NEW GRAPHIC     0     0  1652     0
 354                                  POLAR           0     0  1203     0    24
 355      0        0        0        0 GDT ROUND      0     2  1403     0    25
 356     3                            PARAM           2     0  9981     0
 357   8224                           PARAM           7     0  9981     0
 358       0.00000                    PARAM          55     0  9981     0
 359                                  PARAM TXT      20     0  9982     0
 360   23                             PARAM           3     1  9981     0
 361                                  GDT END         0     0  9983     0
 362 --------------------             TEXT            0     4  1676     0
 363 --------------------              DL TEXT        0     0  9911     0
 364 --------------------              DL TEXT        0     0  9911     0
 365 -----------------                LDL TEXT        0     0  9919     0
 366 The tops are remeasu             TEXT            0     3  1676     0
 367 red +0,050 mm higher              DL TEXT        0     0  9911     0
 368  :                               LDL TEXT        0     0  9919     0
 369 --------------------             TEXT            0     4  1676     0
 370 --------------------              DL TEXT        0     0  9911     0
 371 --------------------              DL TEXT        0     0  9911     0
 372 -----------------                LDL TEXT        0     0  9919     0
 373                                  TEXT            0     1  1676     0
 374 Top no. 1                        TEXT            0     1  1676     0
 375     3.64986     5.56277     7.22842 I-POS        0 11110     0  1101
 376     4.00000     0.00000     1.05000 POSITION IPT 16 11110  1511  1111

 377                                  CIRCLE          0     0  1104  1410
 378 33  2  1  1    1.00000   0.50000 SCANNING MOD    1     7  1530  1330
 379          0     3.00000   0.00000 SCA CLAM MOD    5     1  9911  1911
 380          0     0.00000   0.00000 SCA TARG WIN    7     1  9919  1919
 381 0.01000   33    0    0    0 3  0 SCANNING       16     4  1531  1331
 382     0.00000     0.00000   1.05000  DL SC_MPT     0 11109     0  1911
 383     0.00000   450.00000   0.00000  DL SC_ANG     0     0     0  1911
 384     0.50000     4.90000   0.00000 LDL SC_SPEED   0     0     0  1919

 385                                  N POINT TERM    3     0  1191  1420    26
 386                                  XYZ             0     0  1262     0
 387   0 114    0  26    3    1    8    1 GDT PLOT    0     3  1470     0
 388 STAFPCZ_RUND_U                    DL GDT PLOT    0     0  9911     0
 389     No. 8     0.00470        5000 LDL GDT PLOT   0     0  9919     0
 390                                  NEW GRAPHIC     0     0  1652     0
 391     0.00000     5.00000     1.05000 I-POS        0 11110     0  1101
 392     0.00000     5.00000     5.00000 I-POS        0 11110     0  1101
 393    60.23720     3.26610     5.00000 I-POS        0 11110     0  1101
 394    62.00000     0.00000     1.05000 POSITION IPT 16 11110  1511  1111
```

```
================================================================================
DATE :  09/02/13    W-NAME: LEGO 1x8 brick program b              PAGE : -  9   -
     |      X     |      Y     |      Z     |            |     |     |     |     |
 NO  |----------------------------------------|  Function  | SC2 | SC1 | PCN | CCN | ADR
     |              Dialog                    |            |     |     |     |     |
 NO  |    Nominal      | U.Tol    | L.Tol     |  Function  | SC2 | SC1 | PCN | CCN |
 NO  |          Identification                |  Function  | SC2 | SC1 | PCN | CCN | ADR
================================================================================
 395 Top no. 8                               TEXT            0      1  1676     0

 396                                         CIRCLE          0      0  1104  1410
 397 33   2   1   1     1.00000    0.50000  SCANNING MOD    1      7  1530  1330
 398            0       3.00000    0.00000  SCA CLAM MOD    5      1  9911  1911
 399            0       0.00000    0.00000  SCA TARG WIN    7      1  9919  1919
 400 0.01000    33      0      0     0 3   0 SCANNING       16      4  1531  1331
 401   56.00000       0.00000      1.05000  DL SC_MPT       0 11109     0  1911
 402    0.00000     450.00000      0.00000  DL SC_ANG       0      0     0  1911
 403    0.50000       4.90000      0.00000 LDL SC_SPEED     0      0     0  1919
 404   55.98430       6.18670      1.05000 I-POS            0 11110     0  1101
 405   55.99240       6.20220      5.99800 I-POS            0 11110     0  1101

 406                                         N POINT TERM    3      0  1191  1420   27
 407                                         XYZ             0      0  1262     0
 408    0 114    0  27    3    1    8    1   GDT PLOT        0      3  1470     0
 409 STAFPCZ_RUND_U                            DL GDT PLOT    0      0  9911     0
 410      No. 8      0.00470            5000 LDL GDT PLOT    0      0  9919     0
 411                                         NEW GRAPHIC     0      0  1652     0
 412                                         POLAR           0      0  1203     0   28
 413 --------------------                    TEXT            0      4  1676     0
 414 --------------------                     DL TEXT        0      0  9911     0
 415 --------------------                     DL TEXT        0      0  9911     0
 416 -----------------                       LDL TEXT        0      0  9919     0
 417 Top no. 4 - with inl                    TEXT            0      2  1676     0
 418 et on top:                              LDL TEXT        0      0  9919     0
 419   27.92898       6.06847      6.03770 I-POS            0 11110     0  1101
 420   28.00000       0.00000      1.05000 POSITION IPT    16 11110  1511  1111

 421                                         POINT FILE      0      0  1100  1410
 422 33   2   1   1     1.00000    0.50000  SCANNING MOD    1      7  1530  1330
 423            0       3.00000    0.00000  SCA CLAM MOD    5      1  9911  1911
 424            0       0.00000    0.00000  SCA TARG WIN    7      1  9919  1919
 425 0.01000    33      0      0     0 3   0 SCANNING       16      4  1531  1331
 426   24.00000       0.00000      1.05000  DL SC_MPT       0 11109     0  1911
 427    0.00000     450.00000      0.00000  DL SC_ANG       0      0     0  1911
 428    0.50000       4.90000      0.00000 LDL SC_SPEED     0      0     0  1919

 429    0 PKTN04         U                   FILE TERMIN     0      1  1191  1420
 430   23.98510       5.00000      1.05000 I-POS            0 11110     0  1101
 431   25.90930       5.00000      3.78220 I-POS            0 11110     0  1101

 432                                         CIRCLE          0      0  1104  1410
 433    0 PKTN04         U                   RECALL FILE     0      1  1305     0

 434                                         ZPT RECALL      3      0  1192   430   29
 435                                         XYZ             0      0  1262     0
 436                                         POLAR           0      0  1203     0   30
 437       0           0           0       0 GDT ROUND       0      2  1403     0   31
 438      3                                  PARAM           2      0  9981     0
 439    8224                                 PARAM           7      0  9981     0
 440      0.00000                            PARAM          55      0  9981     0
 441                                         PARAM TXT      20      0  9982     0
```

```
===============================================================================
DATE :  09/02/13   W-NAME: LEGO 1x8 brick program b              PAGE : - 10   -
    |      X     |      Y     |      Z     |             |      |      |      |      |
 NO |------------------------------------- |   Function  | SC2  | SC1  | PCN  | CCN  | ADR
    |             Dialog                   |             |      |      |      |      |
 NO |    Nominal      | U.Tol  | L.Tol     |   Function  | SC2  | SC1  | PCN  | CCN  |
 NO |           Identification             |   Function  | SC2  | SC1  | PCN  | CCN  | ADR
===============================================================================
 442   29                                  PARAM           3      1  9981     0
 443                                       GDT END         0      0  9983     0
 444 --------------------                  TEXT            0      2  1676     0
 445 ------------                          LDL TEXT        0      0  9919     0
 446   0 114   0  29   3   1   8   1       GDT PLOT        0      3  1470     0
 447 STAFPCZ_RUND_U                         DL GDT PLOT    0      0  9911     0
 448     NO.4       0.00530        5000    LDL GDT PLOT    0      0  9919     0
 449                                       NEW GRAPHIC     0      0  1652     0
 450 Top no. 4 -  WITH GA                  TEXT            0      2  1676     0
 451 USS FILTER - 150                      LDL TEXT        0      0  9919     0
 452   1   1   1   0   1   0   0   0       FILTER MOD1     0      1  1185     0

 453                                       CIRCLE          0      0  1104  1410
 454   0 PKTN04       U                    RECALL FILE     0      1  1305     0
 455                                       ZPT RECALL      3      2  1192   430    32

 456 0.00000    0     0  150    0 0   0    LDL FILTER1     0      0  9919     0
 457   0 114   0  32   3   1   8   1       GDT PLOT        0      3  1470     0
 458 STAFPCZ_RUND_U                         DL GDT PLOT    0      0  9911     0
 459     NO. 4      0.00500        5000    LDL GDT PLOT    0      0  9919     0
 460                                       XYZ             0      0  1262     0
 461                                       NEW GRAPHIC     0      0  1652     0
 462                                       POLAR           0      0  1203     0    33
 463       0        0        0        0    GDT ROUND       0      2  1403     0    34
 464     3                                 PARAM           2      0  9981     0
 465   8224                                PARAM           7      0  9981     0
 466      0.00000                          PARAM          55      0  9981     0
 467                                       PARAM TXT      20      0  9982     0
 468   32                                  PARAM           3      1  9981     0
 469                                       GDT END         0      0  9983     0
 470 --------------------                  TEXT            0      4  1676     0
 471 --------------------                   DL TEXT        0      0  9911     0
 472 --------------------                   DL TEXT        0      0  9911     0
 473 -----------------                     LDL TEXT        0      0  9919     0
 474 The tops are remeasu                  TEXT            0      3  1676     0
 475 red -0,050 mm lower                    DL TEXT        0      0  9911     0
 476  :                                    LDL TEXT        0      0  9919     0
 477 --------------------                  TEXT            0      4  1676     0
 478 --------------------                   DL TEXT        0      0  9911     0
 479 --------------------                   DL TEXT        0      0  9911     0
 480 -----------------                     LDL TEXT        0      0  9919     0
 481                                       XYZ             0      0  1262     0
 482                                       TEXT            0      1  1676     0
 483 Top no. 1                             TEXT            0      1  1676     0
 484    3.64986    5.56277    7.22842      I-POS           0  11110     0  1101
 485    4.00000    0.00000    0.95000      POSITION IPT   16  11110  1511  1111

 486                                       CIRCLE          0      0  1104  1410
 487 33  2  1  1   1.00000   0.50000       SCANNING MOD    1      7  1530  1330
 488           0   3.00000    0.00000      SCA CLAM MOD    5      1  9911  1911
 489           0   0.00000    0.00000      SCA TARG WIN    7      1  9919  1919
 490 0.01000  33     0     0    0 3  0     SCANNING       16      4  1531  1331
 491    0.00000    0.00000    0.95000       DL SC_MPT      0  11109     0  1911
```

```
=============================================================================
DATE :  09/02/13    W-NAME: LEGO 1x8 brick program b              PAGE : - 11   -
       |     X     |     Y     |     Z     |            |     |     |     |     |
  NO   |-------------------------------|  Function  | SC2 | SC1 | PCN | CCN | ADR
       |           Dialog              |            |     |     |     |     |
  NO   |   Nominal    | U.Tol  | L.Tol  |  Function  | SC2 | SC1 | PCN | CCN |
  NO   |        Identification         |  Function  | SC2 | SC1 | PCN | CCN | ADR
=============================================================================
 492     0.00000  450.00000    0.00000  DL SC_ANG      0     0     0  1911
 493     0.50000    4.90000    0.00000 LDL SC_SPEED    0     0     0  1919

 494                                   N POINT TERM    3     0  1191  1420   35
 495                                   XYZ             0     0  1262     0
 496    0 114   0  35   3   1   8   1  GDT PLOT        0     3  1470     0
 497 STAFPCZ_RUND_U                     DL GDT PLOT    0     0  9911     0
 498      No. 8      0.00470       5000 LDL GDT PLOT   0     0  9919     0
 499                                   NEW GRAPHIC     0     0  1652     0
 500     0.00000    5.00000    0.95000 I-POS           0 11110     0  1101
 501     0.00000    5.00000    5.00000 I-POS           0 11110     0  1101
 502    60.23720    3.26610    5.00000 I-POS           0 11110     0  1101
 503    62.00000    0.00000    0.95000 POSITION IPT   16 11110  1511  1111
 504 Top no. 8                         TEXT            0     1  1676     0

 505                                   CIRCLE          0     0  1104  1410
 506 33   2   1   1    1.00000   0.50000  SCANNING MOD 1     7  1530  1330
 507            0    3.00000    0.00000 SCA CLAM MOD   5     1  9911  1911
 508            0    0.00000    0.00000 SCA TARG WIN   7     1  9919  1919
 509 0.01000    33      0      0    0 3   0 SCANNING  16     4  1531  1331
 510    56.00000    0.00000    0.95000  DL SC_MPT      0 11109     0  1911
 511     0.00000  450.00000    0.00000  DL SC_ANG      0     0     0  1911
 512     0.50000    4.90000    0.00000 LDL SC_SPEED    0     0     0  1919
 513    55.98430    6.18670    0.95000 I-POS           0 11110     0  1101
 514    55.99240    6.20220    5.99800 I-POS           0 11110     0  1101

 515                                   N POINT TERM    3     0  1191  1420   36
 516                                   XYZ             0     0  1262     0
 517    0 114   0  36   3   1   8   1  GDT PLOT        0     3  1470     0
 518 STAFPCZ_RUND_U                     DL GDT PLOT    0     0  9911     0
 519      No. 8      0.00470       5000 LDL GDT PLOT   0     0  9919     0
 520                                   NEW GRAPHIC     0     0  1652     0
 521                                   POLAR           0     0  1203     0   37
 522 --------------------              TEXT            0     4  1676     0
 523 --------------------               DL TEXT        0     0  9911     0
 524 --------------------               DL TEXT        0     0  9911     0
 525 -----------------                 LDL TEXT        0     0  9919     0
 526 Top no. 4 - with inl              TEXT            0     2  1676     0
 527 et on top:                        LDL TEXT        0     0  9919     0
 528    27.92898    6.06847    6.03770 I-POS           0 11110     0  1101
 529    28.00000    0.00000    0.95000 POSITION IPT   16 11110  1511  1111

 530                                   POINT FILE      0     0  1100  1410
 531 33   2   1   1    1.00000   0.50000  SCANNING MOD 1     7  1530  1330
 532            0    3.00000    0.00000 SCA CLAM MOD   5     1  9911  1911
 533            0    0.00000    0.00000 SCA TARG WIN   7     1  9919  1919
 534 0.01000    33      0      0    0 3   0 SCANNING  16     4  1531  1331
 535    24.00000    0.00000    0.95000  DL SC_MPT      0 11109     0  1911
 536     0.00000  450.00000    0.00000  DL SC_ANG      0     0     0  1911
 537     0.50000    4.90000    0.00000 LDL SC_SPEED    0     0     0  1919

 538    0 PKTN04       U               FILE TERMIN     0     1  1191  1420
 539    23.98510    5.00000    0.95000 I-POS           0 11110     0  1101
```

```
================================================================================
DATE :   09/02/13   W-NAME: LEGO 1x8 brick program b              PAGE : - 12   -
     |      X     |      Y     |      Z     |            |      |      |      |      |
 NO  |-----------------------------------------|  Function  | SC2  | SC1  | PCN  | CCN  | ADR
     |              Dialog                  |            |      |      |      |      |
 NO  |    Nominal    | U.Tol    | L.Tol     |  Function  | SC2  | SC1  | PCN  | CCN  |
 NO  |            Identification            |  Function  | SC2  | SC1  | PCN  | CCN  | ADR
================================================================================
 540   26.90930     5.00000     5.00000 I-POS            0 11110    0  1101

 541                                    CIRCLE           0     0  1104  1410
 542   0 PKTN04        U                RECALL FILE      0     1  1305     0

 543                                    ZPT RECALL       3     0  1192   430   38
 544                                    XYZ              0     0  1262     0
 545                                    POLAR            0     0  1203     0   39
 546       0        0        0        0 GDT ROUND        0     2  1403     0   40
 547      3                             PARAM            2     0  9981     0
 548   8224                             PARAM            7     0  9981     0
 549      0.00000                       PARAM           55     0  9981     0
 550                                    PARAM TXT       20     0  9982     0
 551   38                               PARAM            3     1  9981     0
 552                                    GDT END          0     0  9983     0
 553 --------------------               TEXT             0     2  1676     0
 554 ------------                       LDL TEXT         0     0  9919     0
 555   0 114   0  38   3   1   8   1   GDT PLOT         0     3  1470     0
 556 STAFPCZ_RUND_U                      DL GDT PLOT     0     0  9911     0
 557     NO.4       0.00530        5000 LDL GDT PLOT     0     0  9919     0
 558                                    NEW GRAPHIC      0     0  1652     0
 559 Top no. 4 -  WITH GA               TEXT             0     2  1676     0
 560 USS FILTER - 150                   LDL TEXT         0     0  9919     0
 561   1   1   1   0   1   0   0   0   FILTER MOD1      0     1  1185     0

 562                                    CIRCLE           0     0  1104  1410
 563   0 PKTN04        U                RECALL FILE      0     1  1305     0
 564                                    ZPT RECALL       3     2  1192   430   41

 565 0.00000     0     0  150     0 0  0 LDL FILTER1     0     0  9919     0
 566   0 114   0  41   3   1   8   1   GDT PLOT         0     3  1470     0
 567 STAFPCZ_RUND_U                      DL GDT PLOT     0     0  9911     0
 568     NO. 4      0.00500        5000 LDL GDT PLOT     0     0  9919     0
 569                                    XYZ              0     0  1262     0
 570                                    NEW GRAPHIC      0     0  1652     0
 571                                    POLAR            0     0  1203     0   42
 572       0        0        0        0 GDT ROUND        0     2  1403     0   43
 573      3                             PARAM            2     0  9981     0
 574   8224                             PARAM            7     0  9981     0
 575      0.00000                       PARAM           55     0  9981     0
 576                                    PARAM TXT       20     0  9982     0
 577   41                               PARAM            3     1  9981     0
 578                                    GDT END          0     0  9983     0
 579 --------------------               TEXT             0     4  1676     0
 580 --------------------                DL TEXT         0     0  9911     0
 581 --------------------                DL TEXT         0     0  9911     0
 582 -----------------                  LDL TEXT         0     0  9919     0
 583                                    TEXT             0     1  1676     0
 584 --------------------               TEXT             0     2  1676     0
 585 ------------                       LDL TEXT         0     0  9919     0
 586 CHECK Z PLANE ZERO.                TEXT             0     1  1676     0
 587 --------------------               TEXT             0     2  1676     0
 588 ------------                       LDL TEXT         0     0  9919     0
```

```
================================================================================
DATE :  09/02/13   W-NAME: LEGO 1x8 brick program b            PAGE : - 13   -
    |     X     |     Y     |     Z     |            |     |     |     |     |
 NO |-------------------------------|  Function  | SC2 | SC1 | PCN | CCN | ADR
    |            Dialog             |            |     |     |     |     |
 NO |    Nominal      |  U.Tol  | L.Tol |  Function  | SC2 | SC1 | PCN | CCN |
 NO |          Identification       |  Function  | SC2 | SC1 | PCN | CCN | ADR
================================================================================
 589   -3.00000    3.00000    5.00000 POSITION IPT     8 11110  1511  1111
 590   28.00000    5.00000  180.00000 I-POS            0 11110     0  1101
 591 --------------------             TEXT             0     4  1676     0
 592 --------------------              DL TEXT         0     0  9911     0
 593 --------------------              DL TEXT         0     0  9911     0
 594 ----------------                 LDL TEXT         0     0  9919     0
 595 YE                               TIME STAMP       0     1  1618     0
 596                                  P-END            0     0  9999  1999
```

5.1.1.8. Example on the measurement protocol for Item 2

```
-----------------------------------------------------------------------------------------------

    C A R L   Z E I S S  /  C A L Y P S O  5.0.20.00          Compact Printout
-----------------------------------------------------------------------------------------------
Measurement Plan            Operator        Date                Incremental Part Number
Dosage tube CT comparison ALL               May 2, 2013         Recalibration Dosage tube Part 26-12
MC
-----------------------------------------------------------------------------------------------
Names                   Description   Actual       Nominal    Utol      Ltol   Dev.      Histogr.
===============================================================================================

Cylinder Datum A("Alignment1")
                         Least Squares Cylinder      #P    (16)  External
S=  0.0045                Min=(16)      -0.0070      Max=(6)    0.0048    Form=     0.0118
                          Z              0.0002       0.0000
                          X              0.0003       0.0000
                          Y             18.0000      18.0000
                          D              4.1120       4.1000
                          A1 Z/Y        -0.0004       0.0000
                          A2 X/Y        -0.0025       0.0000

2-D Line2("Symmetry1")    Least Squares 2-D Line     #P      (3)
S=  0.0004                Min=(1)       -0.0003      Max=(2)    0.0004    Form=     0.0006
                          Y              0.9663       1.0000
                          Z             -3.1445      -3.1000
                          X             -0.3997      -0.4000
                          A1 Y/X         0.4044       0.5000
                          A2 Z/X         0.0317       0.0000

2-D Line3("Symmetry1")    Least Squares 2-D Line     #P      (3)
S=  0.0004                Min=(3)       -0.0002      Max=(2)    0.0003    Form=     0.0005
                          Y              1.0348       1.0000
                          Z              3.1533       3.1577
                          X             -0.7076      -0.7073
                          A1 Y/X         0.4651       0.4517
                          A2 Z/X        -0.0411       0.0000

Symmetry1                 2-D Line *                Symmetry
                          Y              1.0007       0.9999
                          Z              0.0043       0.0289
                          X             -0.5537      -0.5536
                          A1 Y/X         0.4348       0.4759
                          A2 Z/X        -0.0047       0.0000

Plane Datum B("Alignment1")
                         Least Squares Plane         #P     (8)
S=  0.0003                Min=(5)       -0.0004      Max=(7)    0.0004    Form=     0.0008
                          Y             -0.0015       0.0016
                          Z             -2.5714      -2.5296
                          X             -0.9092      -0.9115
                          A1 X/-Y       -0.0060      -0.1000
                          A2 Z/-Y        0.0220      -0.0012

Alignment1                Alignment
Spatial Rotation          Cylinder Datum A
Planar Rotation           Symmetry1
X Origin                  Cylinder Datum A
Y Origin                  Plane Datum B
Z Origin                  Cylinder Datum A

 X                                       0.0011          Tilt Direction X/Z              351.3809
 Y                                      -0.0006          Angle Of Inclination              0.0026
 Z                                       0.0003          Plane Angle X/Z                   8.6238
 Delta Value                             0.0023          Plane rotation                    0.0047

Cylinder Datum A("Cylindricity Datum A")
                         Minimum Zone Cylinder       #P    (16)  External
S=  0.0047                Min=(11)      -0.0052      Max=(2)    0.0052    Form=     0.0104
                          Z             -0.0001       0.0000
                          X              0.0018       0.0000
                          Y             18.0000      18.0000
                          D              4.1110       4.1000
                          A1 Z/Y         0.0027       0.0000
```

C A R L Z E I S S / C A L Y P S O   5.0.20.00   COMPACT PRINTOUT   -2-

Measurement Plan	Operator	Date	Part No
Dosage tube CT comparison MC	ALL	May 2, 2013	Recalibration D

Names	Description	Actual	Nominal	Utol	Ltol	Dev.	Histogr.
	A2 X/Y	-0.0091	0.0000				
Cylindricity Datum A	GDT Cyl			0.0500		0.0104	|-
Circle D1("Diameter_Circle D1")							
	Least Squares Circle		#P	(24)	Internal		
S= 0.0009	Min=(22)	-0.0013	Max=(12)	0.0021	Form=	0.0034	
	Z	0.0049	0.0000				
	X	-0.0058	0.0000				
	Y	1.9984	2.0000				
Diameter_Circle D1	D	3.4052	3.4000	0.0500	-0.0500	0.0052	|-
Roundness_Circle D1	GDT Roun			0.0200		0.0034	|-
Circle D2("Diameter_Circle D2")							
	Least Squares Circle		#P	(24)	Internal		
S= 0.0040	Min=(7)	-0.0064	Max=(1)	0.0059	Form=	0.0122	
	Z	0.0024	0.0000				
	X	-0.0042	0.0000				
	Y	11.9985	12.0000				
Diameter_Circle D2	D	3.4107	3.4000	0.0500	-0.0500	0.0107	|-
Roundness_Circle D2	GDT Roun			0.0200		0.0122	|---
Plane2("Intersection2")	Least Squares Plane		#P	(24)			
S= 0.0017	Min=(21)	-0.0029	Max=(15)	0.0021	Form=	0.0050	
	Y	46.3847	46.3000				
	Z	-1.8322	-2.4000				
	X	-1.7949	-1.9000				
	A1 Z/Y	0.0183	-0.8000				
	A2 X/Y	-0.0255	0.5000				
Intersection2	Point *		Intersection				
	X	0.0000	0.0000				
	Y	46.3849	46.3169				
	Z	0.0000	0.0000				
Intersection1	Point *		Intersection				
	X	0.0011	0.0000				
	Y	-0.0006	0.0000				
	Z	0.0003	0.0000				
Distance L1	CartDist	46.3849	46.4000	0.0500	-0.0500	-0.0151	--|
Plane2("Flatness L1")	Minimum Zone Plane		#P	(24)			
S= 0.0017	Min=(1)	-0.0024	Max=(12)	0.0024	Form=	0.0049	
	Y	46.3843	46.3000				
	Z	-1.8322	-2.4000				
	X	-1.7950	-1.9000				
	A1 Z/Y	0.0178	-0.8000				
	A2 X/Y	-0.0238	0.5000				
Flatness L1	GDT Flat			0.0500		0.0049	|-